DEVELOPMENT OF A GEOMORPHIC MODEL TO PREDICT EROSION OF PRE-DAM COLORADO RIVER TERRACES CONTAINING ARCHAEOLOGICAL RESOURCES

BOR Cooperative Agreement No. 1425-98-FC-40-22610

Prepared for

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SWCA Project No. 2362-1383
SWCA Cultural Resources Report No. 99-257

February 18, 2000

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ACKNOWLEDGMENTS

A number of people contributed in a variety of ways toward the successful completion of this report, many of them in more than one capacity. Steve Carothers and Rich Valdez helped get us started with the initial research design. Rich Durnan advised us on database development. Duane Hubbard and Diane Boyer directed us toward important historical photo archives. Helen Wadsworth, GCMRC Librarian, provided us with a plethora of air photos from GCMRC files. Bob Webb, Jack Schmidt, and Ruth Lambert advised us on hypothesis testing. Lisa Leap, Richard Hereford, and Stephanie Yard acted as our technical advisors throughout the length of the project.

We thank those who made the effort to review and comment on the draft final report: Rich Hereford, Ruth Lambert, Lisa Leap, Stephanie Yard, and nine anonymous reviewers. Their prodigious comments made the final report a better product, while we take full responsibility for the ideas and results contained therein.

Field-support staff were essential for their advice and assistance on the ground. Lisa Leap, of the Grand Canyon River Corridor Monitoring Project, directed us to our areas of study in Grand Canyon. Bob Webb, John Weisheit, and Steve "Teaberry" Young provided help in locating field areas in Cataract Canyon. Steve Wiele consulted with us on river dynamics and sediment transport at several of our type geomorphic settings. Mark Gonzales and Steve Lamphear trained us to conduct field survey work in Grand Canyon and Cataract Canyon. Steve Lamphear was particularly helpful in producing the topographic maps of the type geomorphic settings. Chris Brod, Rebecca Seago, and John Douglass were instrumental in producing the survey results. And, of course, we could not have carried out this project without our sterling field assistants, who worked hard to successfully complete fieldwork on our river trips: Laurie Lewis, John Sterling, Kathy Durham, Bill Hatcher, Rich Durnan, H. J. Schmidt, Ally Martinez, Lynn Neal, Lissa Bartlett, Robert O'Brien, Rebecca Seago, Matt Johnson, Helen Fairley, and Billy Ellwanger. Finally, our greatest appreciation goes to Gary O'Brien, who helped tremendously in getting us down the river and counseled us through all our crises of data collection.

ABSTRACT

Most of the cultural history of the Colorado River corridor in Grand Canyon is preserved in high river terraces below Glen Canyon Dam that are no longer flooded by the dam-controlled river. Apparent increased rates of gully erosion and loss of cultural sites in these terraces have been attributed to base-level effects caused by dam operations and/or climatic variation. Two avenues of investigation are pursued here. First, we address in the form of hypotheses three questions concerning gully erosion of archaeological terraces: (1) Has the amount of erosion increased in the post-dam period? (2) Can an apparent increase in erosion be attributed to climatic variation? (3) Does the presence and/or operation of the dam contribute to an apparent increase in erosion? Second, we develop a conceptual geomorphic model that describes the variety of processes that operate in the small-catchment system and provide a mathematical model that predicts relative vulnerability of terraces to gully erosion at various small catchments.

We followed several lines of inquiry to address these issues. We selected a sample set of 119 small catchments in Grand Canyon for field investigations and data collection. We classified these catchments into five distinctive geomorphic settings and examined them for process-response relations that affect gully development. Air photo sequences from 1965 to the present provided evidence to determine the extent of gully development in Grand Canyon since the dam was completed in 1963. Selection of a control reach in Cataract Canyon with an ecosystem that is analogous to that of the pre-dam river in Grand Canyon allowed us to investigate small-catchment and river processes as they may have interacted in the pre-dam setting.

A review of the work of previous researchers shows that a climatic pulse of particularly high warm-season and winter rainfall has occurred since 1978 but that such perturbations are not unique in the climatic record (Hereford and Webb 1992; Webb, Griffiths, and Melis 2000). Similar pulses occurred during the first three decades of the century and for a short period during the early 1940s. Results of our analysis and examination of climate for the three decades before and three decades after dam construction show that, although local areas vary from one another, warm-season precipitation patterns across the southern Colorado Plateau have changed little. Air photo analysis in Grand Canyon and investigations in Cataract Canyon show that gully erosion has increased in Grand Canyon during the past two decades in comparison with probable conditions in the several previous decades. It can be assumed that periods of high precipitation earlier in the century also formed extensive gullies, yet analysis of 1965 air photos shows little evidence for this, indicating that alluvial deposition in the pre-dam period was probably responsible for restoring sand to gullies. Therefore, the recent period of high precipitation may not be the sole cause of accelerated gully degradation observed in the past two decades.

The "base-level hypothesis" of Hereford and others (1993) states that the interruption of high sediment flux and large annual floods by the presence of Glen Canyon Dam in Grand Canyon has changed dynamic equilibrium conditions at the mouths of gullies and arroyos, resulting in accelerated rates of gully erosion. Our work in the control section of Cataract Canyon and in Grand Canyon shows that this hypothesis needs refinement. The relative absence and small size of gullies in Cataract Canyon suggests that conditions are intrinsically different from those now present in Grand Canyon, despite geomorphic and climatic similarity between the two reaches.

It is apparent that before emplacement of the dam gully degradation in terraces was restored by periodic alluvial deposition from river floods, but perhaps even more important is the redistribution of flood sands onto higher terraces by wind. Thus, we propose the term "restorative base-level hypothesis" to emphasize the dynamic equilibrium between gully erosion and renewed deposition, a process that remains active in Cataract Canyon but is disrupted in Grand Canyon by the presence and operation of the dam.

We developed type geomorphic settings to develop a conceptual process model for the diverse small-catchment geomorphic system in Grand Canyon. Research findings explain how streams are able to cross broad, flat terraces given a rainfall event and how they become progressively more integrated with the river. The primary channelization processes are ponding and overflow, alluvial fan progradation, and infiltration and piping, all of which contribute to nickpoint migration. An understanding of these processes was essential to building the geomorphic model.

The predictive mathematical model quantifies erosional vulnerability by applying a hypothetical rainfall event of 25 mm/hour onto a catchment above a "pristine" terrace sequence. The principal driving factor for erosion is basin area. The principal resisting factor for erosion is terrace diffusion capacity, which is a function of terrace sand cross-sectional area and infiltration capacity. Several important modifying factors are applied to the basic model to determine relative vulnerability of each terrace to gully erosion. Vulnerability of the top terrace at each catchment is plotted against the measured amount of gully erosion in that terrace, providing a base line against which progressive changes in gully depth can be easily monitored in the future.

Field studies and research show that: (1) gully erosion of terraces has been severe during the past 20 years in Grand Canyon due to unusually high precipitation; and (2) sediment deprivation coupled with the lack of large annual floods has caused a reduction in restorative (depositional) factors. Continued measurement and documentation of geomorphic processes in catchments, particularly at type geomorphic settings, will further refine and verify the predictability of the model. We conclude that beach-habitat-building flows are essential for initiating natural restorative processes and that one of the most important processes in gully mitigation may be eolian reworking of newly deposited flood sands onto higher terraces. Prior to the construction of Glen Canyon Dam, gully-deepening and river/wind depositional processes were in dynamic equilibrium, allowing the preservation of ancient cultural sites for the past several thousand years.

CHAPTER 1

INTRODUCTION

Kate S. Thompson and Andre R. Potochnik

The study reported here was commissioned by the Cultural Resources Program of the Grand Canyon Monitoring and Research Center (GCMRC), the technical arm of the Adaptive Management Program that assesses the effects of the operations of Glen Canyon Dam on downstream resources, to address the processes of gully erosion in archaeologically rich river terraces along the Colorado River in Grand Canyon. Previous workers have proposed that erosion of these sand terraces has been accelerated since emplacement of Glen Canyon Dam and that the dam and its operations are partly responsible for this change (Fairley et al. 1994; Hereford et al. 1993; Lucchitta and Leopold 1999). Others have proposed that decadal-scale climate change may be responsible for the apparent rapid erosion of these terraces (Hereford and Webb 1992; J. Schmidt, personal communication 1998; R. H. Webb, personal communication 1998). Lastly, there remains the possibility that the apparent acceleration of erosion of cultural features is simply continuing at pre-dam rates and processes and that the dam has no influence on the geomorphic system.

Whatever the cause, valuable archaeological resources are being lost to erosion, a matter of regulatory, legislative, and ethical concern to government agencies, tribal groups, archaeological researchers, preservationists, and the general public. In particular, the resource management entities of Grand Canyon National Park (GRCA), the Bureau of Reclamation (BOR), the Arizona State Historic Preservation Office (SHPO), the Advisory Council on Historic Preservation, the GCMRC, and six Native American tribes (the Hopi Tribe, the Hualapai Nation, the Kaibab Band of Paiute Indians, the Paiute Indian Tribe of Utah for the Shivwits Band of Paiutes, the Navajo Nation, and the Pueblo of Zuni) are mandated to preserve and mitigate impacts to these cultural resources. Meeting this mandate calls for a thorough understanding of the geomorphic system, the causes of erosion, and the development of a model that can predict the relative vulnerability of cultural sites to gully erosion.

We investigated how the presence or operations of Glen Canyon Dam may be directly or indirectly impacting archaeological and other cultural properties along the Colorado River corridor within Grand Canyon. A cultural property is any prehistoric or historic material or feature that represents human habitation or use along the river. The objectives of this study were threefold: (1) to test hypotheses that may explain the apparent increased erosion rates at cultural sites on river terraces; (2) to develop a predictive geomorphic model useful as a tool for long-term monitoring, preservation, and mitigation of these resources; and (3) to identify the most threatened sites so that GRCA managers can prioritize remedial action needs. We were able to compare model predictions with on-site field evaluations to test the validity of our model. Furthermore, we discuss how monitors can use this model as a practical predictive tool for anticipating the vulnerability of sites to incipient degradation.

The National Park Service (NPS) mandate under Section 110 of the National Historic Preservation Act (NHPA) requires preservation of the integrity of these resources for the public, with serious consideration given to Native American concerns for cultural resource management and preservation. To facilitate compliance with the BOR's responsibilities under Section 106 of NHPA, a Programmatic Agreement (PA) was signed in 1994 by various federal and state agencies and the six Native American groups listed above. The Grand Canyon Protection Act of 1992 (Section 1802) specifies that Glen Canyon Dam "shall be operated in such a manner as to protect, mitigate adverse impacts to, and improve the values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established, including, but not limited to, natural and cultural resources and visitor use."

Research conducted under Glen Canyon Environmental Studies Phase II during the early 1990s documented degradation of numerous sites within the old high-water zone (OHWZ) of the pre-dam period (Carothers and Brown 1991; Fairley et al. 1994). This finding prompted Hereford and colleagues (1993) to formulate the "base-level hypothesis": that site degradation is fundamentally caused by rainfall-induced erosion of the pre-dam terraces and is accelerated by degradation of sand bars fronting these terraces. These sand bars, located at the "toes" of the culturally rich pre-dam terraces, served as buttresses in the pre-dam period, slowing downcutting by small tributary streams that drain onto the higher terraces.

Before the dam, annual sediment-laden floods periodically renewed these lower terraces and presumably infilled incipient gullies. The ten-year flood of about 140,000 cubic feet per second (cfs) (O'Connor et al. 1994) maintained a higher local base level of sand bars and thus minimized the rate of downcutting by gullies and arroyos (Hereford et al. 1993; Hereford 1996). Many streams that once drained onto a higher terrace level have recently breached the lower terraces and now drain to the Colorado River as river-based streams (Leap et al. 2000). Erosion and non-renewal of sediment in the river corridor have disrupted the balance between gully erosion and annual deposition/infilling of river sediments in those catchments. The drop in local "effective" base level for these streams results in deepening and widening of existing gullies (Higgins, Hill, and Lehre 1990; Schumm 1977), with consequent loss of cultural resources contained within the higher terraces (Hereford et al. 1993).

The draft Historic Preservation Plan (HPP) (Bureau of Reclamation [BOR] et al. 1997) targets the need for a refined understanding of erosional processes and in particular calls for "a predictive model of geomorphic processes related to archaeological site erosion." The current study focused on testing three hypotheses of accelerated gully erosion in the post-dam period, creation of a predictive geomorphic model to identify site vulnerability to gully erosion related to selected archaeological sites, and prioritizing existing sites in a risk-hierarchy system.

STUDY OBJECTIVES

Significance of Work

Essential to protecting cultural resources along the Colorado River is the understanding of geomorphic processes that are directly or indirectly related to the operations of the dam. In our research we sought a more accurate understanding of pre-dam depositional and erosional events as a basis for determining whether specific erosional processes are related to dam operations. As stated in the draft HPP, this effort will help close gaps in the Cultural Resource Monitoring Program (CRMP) database by integrating archaeological findings with the geomorphic model, thereby assisting in preservation of cultural sites along the river corridor.

Specific Objectives and Hypotheses

The specific objectives of the study were:

1. To evaluate data from previous geomorphic work on river- and terrace-based arroyos, archaeological monitoring, and sedimentation and climate studies, incorporating relevant research into three primary sets of hypotheses.

2. To test the null hypothesis (H_0): that terrace erosion rates and gully erosion rates on the terraces have remained unchanged from pre-dam time to post-dam time.
   (a) Report on river-level air photo analysis to determine timing for the inception of the largest gullies in pre-dam terraces
   (b) Compare amount of gully erosion on terraces of a control section of river (Cataract Canyon) that emulates the alluvial history and the pre-dam geomorphic setting in Grand Canyon

3. To determine if H_0 is falsifiable based on research findings.

4. To test the alternate hypothesis (H_1): that gully erosion on alluvial terraces associated with archaeology has increased from pre-dam time to post-dam time due to variation in precipitation patterns.
   (a) Evaluate previous research on decadal-scale precipitation variations that may be responsible for increased erosion rates.
   (b) Investigate variations in monsoon-season rainfall at equivalent time periods before and after closure of Glen Canyon Dam

5. To test the alternate parallel hypothesis of Hereford et al. 1993 (H_2): that gully erosion on alluvial terraces associated with archaeology has increased from pre-dam time to post-dam time due to base-level effects.

(a) Report on rebuilding of sand bars that buttress upper terraces and infill gullies in both Grand Canyon and the control section of Cataract Canyon
(b) Report on process of gully erosion and integration with the river at a large number of archaeological sites in Grand Canyon

6. To develop a geomorphic model that explains the apparent increased rates of gully erosion and more clearly defines our understanding of how gully erosion is likely to impact archaeological resources in the future.

7. To develop a predictive geomorphic model that ranks each site as to its vulnerability to erosion.

8. To identify for remedial action the sites where resources are most threatened.

9. To evaluate and discuss how the project results can be used in the monitoring program to aid in protecting the most-threatened resources.

Value of Anticipated Results

To test the three hypotheses, we examined the concepts outlined by Hereford et al. (1993), who suggest that erosion of culturally rich pre-dam river terraces is a direct response (1) to rainfall and (2) to base-level change, a consequence of the presence and operation of the dam. We apply this hypothesis at each study site and test, as best as resources allow, the null hypothesis: that gully (arroyo) erosion has not increased in post-dam time. Other investigators have suggested that base-level factors are generally over-emphasized and that other drainage integration mechanisms or climatic patterns are often more important (Lucchitta 1991; J. Schmidt and R. H. Webb, personal communication 1998). Nonetheless, Hereford and colleagues have produced a series of papers (Hereford et al. 1993; Hereford et al. 1996) and maps (Hereford 1996; Hereford, Burke, and Thompson 1998, 2000a, 2000b) describing the stratigraphy and geomorphic context of the pre-dam alluvial terraces and have set the stage for further important investigations. Our study expands on the types of geomorphic processes that operate in this small-catchment, ephemeral-stream geomorphic system and discusses their relative importance. This report also provides cultural resource managers and constituencies with a practical predictive tool for anticipating the vulnerability of sites to incipient degradation.

BACKGROUND

Previous Archaeological and Geomorphic Studies

Early surveys of archaeological sites along the river were conducted by Taylor (1958), Euler and Taylor (1966), Jett (1968), and Schwartz, Chapman, and Kepp (1980). Archaeological survey efforts intensified in the early 1980s, when extraordinarily high river flows, combined with increased human visitation, began to profoundly impact sites along the river. In 1984 Jones (1985) conducted an excavation of five sites and recognized that little was known of the stratigraphic context and geomorphology of these sites. Because of concerns over degradation of cultural resources, the first comprehensive documentation of archaeological sites was performed throughout the length of Grand Canyon (255 river miles) at or below the 300,000 cfs stage height (Fairley et al. 1994). Between Lees Ferry and Separation Canyon, 475 prehistoric and historic sites were catalogued, 265 of which are on or in Colorado River alluvium. Most of these alluvial sites are in the broader geomorphic reaches described by Howard and Dolan (1981) and Schmidt and Graf (1990), such as "Furnace Flats" and "Western Grand Canyon" (Figure 1.1).

Figure 1.1. Areas showing concentrations of archaeological sites within geomorphic reaches of Grand Canyon. Cataract Canyon is the control area of study.

The geomorphology associated with archaeological sites along the Colorado River corridor was investigated by Hereford (1996), Hereford et al. (1993), Hereford, Burke, and Thompson (1998), Lucchitta (1991), Lucchitta et al. (1995a), Lucchitta et al. (1995b), and Lucchitta and Leopold (1999). These researchers identified periods of deposition and erosion from Quaternary times to the present by mapping the great variety of these depositional sequences along the river corridor. Detailed mapping of specific sites has provided an understanding of geomorphic processes affecting these deposits, which has, in turn, allowed the formulation of a hypothesis that attempts to explain the accelerated erosion of associated archaeological sites. Stratigraphic profiles developed by Hereford and others (1993, 1996) (synthesized in Figure 1.2) illustrate a sequence of river flood sands interbedded with slopewash or tributary deposits. Interestingly, these deposits contain cut-and-fill features that suggest a dynamic process of channel erosion and subsequent infilling by river flood sand in the pre-dam era. Post-dam alluvium typically contains only channel cuts, suggesting net erosion since emplacement of the dam. While erosion to the archaeological terrace was evident in pre-dam time, it was generally healed periodically with an influx of river or eolian sediment. Hereford and others (1993) therefore deduced that erosion of pre-dam alluvial terraces is an indirect result of dam operations, but they have been criticized for not establishing a control site for comparison outside the Grand Canyon where the river is largely without dams.

Figure 1.2. Schematic cross section of river terrace sequence with various geomorphic features (after Hereford et al. 1993, 1996).

Hereford and others (1993, 1996) described and synthesized the late Holocene alluvial terrace stratigraphy in four discrete study areas of the Furnace Flats reach of Grand Canyon. In these areas, pre-dam alluvial terraces comprise an extensive geomorphic system that interfaces with two adjacent geomorphic systems: the tributary alluvial fan system (Hereford et al. 1996; Webb, Pringle, and Rink 1989) and the river channel system (Rubin, Schmidt, and Moore 1990; Schmidt 1990; Schmidt and Graf 1990) (Figure 1.2). Hereford, Thompson, and Burke (1997, 1998) developed methods for dating Late Holocene debris fans by integrating archaeological and radiocarbon techniques from adjacent fluvial terraces. In addition, they published detailed geologic maps of five major tributary fan complexes: Lees Ferry (Hereford, Burke, and Thompson 2000a), Nankoweap Creek (Hereford, Burke, and Thompson 1998), Palisades Creek (Hereford 1996), and Lower Tanner Canyon and Granite Park (Hereford, Burke, and Thompson 2000b) that illustrate the late Holocene stratigraphy.

Researchers (Hereford et al. 1993; Lucchitta et al. 1995b) have also described various geomorphic processes affecting the pre-dam alluvial terraces, particularly the effects of local ephemeral stream networks that cross the terraces. Hereford and others (1993) distinguished terrace-based streams from river-based streams, depending on whether the stream terminates on a pre-dam alluvial terrace or is integrated with the river or a major tributary to the river. They noted that river-based streams had cut deep arroyos in the sandy pre-dam terraces, exposing and eroding numerous archaeological sites. These researchers also suggested the possible effects of local climatic variations (Hereford and Webb 1992) that have been eroding pre-dam alluvial terraces containing most of the prehistoric and historic cultural sites. However, all concur that Glen Canyon Dam has exacerbated a possible natural cycle of erosion by further decreasing the sediment supply to the river.

Rationale for This Study

Hereford and others (1993, 1996) pointed out the need to understand cause-and-effect relationships between the pre-dam alluvial terrace system and post-dam water flows and associated deposits. Before regulation of the Colorado River, most small ephemeral streams probably drained to a higher local base level, represented by the pre-dam terraces. If any streams drained to the river, they were infilled with eolian sand or river sand from a large flood, as evidenced by cut-and-fill structures identified in pre-dam terraces such as that recorded at Locality 1 of the Palisades Creek area (Hereford 1996). Under pre-dam conditions, sand and silt deposited in the mouths of small tributary channels during annual floods would infill previously eroded headcuts, thus preventing them from migrating up-channel. Because regulated flows have lowered the level at which river sand bars are deposited, small streams are regrading to a lower "effective" base level. The concept of base-level change invoking gullying or arroyo-cutting is a well-known concept that has been employed with equilibrium of streams (Gilbert 1879; Leopold and Bull 1979). With local intense rainfall as the driving force, channels are presently extending headward and widening as they adjust to the new post-dam base level of sand-bar building. Once streams reach this configuration, erosion of upper terraces is greatly accelerated, rendering remedial efforts difficult, if not fruitless.

If the base-level hypothesis is correct, the size and characteristics of channel-margin sand bars along the river are of critical importance in determining extent of erosion of cultural sites. We would expect that areas with persistent sand bars would maintain the base level of streams. Gullies can be infilled or buried, and wind can rework sediment, often mounding it onto the next higher terrace (Hereford 1996; Hereford, Burke, and Thompson 1998). A model for sediment transport and deposition by the post-dam river was produced by Rubin, Schmidt, and Moore (1990), Schmidt (1990), and Schmidt and Graf (1990). The continuing monitoring work of Kaplinski et al. (1993) evaluates changing conditions of sand bars along the river under different flow regimes. Modeling of the 1996 flood deposited sands by Wiele (1997) and Yeatts (1996, 1998) helps to determine the utility of a controlled flood as a management tool. These studies are extremely important in predicting the longevity of the pre-dam terraces in the post-dam regime.

The changing conditions of large tributary alluvial fans, which lie adjacent to the sandy alluvial pre-dam terraces, will determine whether some of the small ephemeral streams become integrated with the river via the fans. As cited in several reports (BOR et al. 1997; Leap et al. 1998; Neal 2000), a predictive model is needed for properly assessing erosional risk to archaeological sites. Therefore, any geomorphic model that attempts to predict erosion of the pre-dam alluvial terrace system will need to investigate the important effects of base-level control from both channel margin bars and alluvial fans.

To date, no formal geomorphic model ranking vulnerability of archaeological sites to erosion has been fully developed. Recorded observations by River Corridor Monitoring Program (RCMP) archaeologists working in the Grand Canyon (Leap et al. 2000) and in Glen Canyon provide a record of erosion since 1992. While these data provide good qualitative documentation of change, there are deficiencies in quantifying the amount and extent of erosional change within a site, from site to site, and from year to year (Neal 2000). These deficiencies have been directly related to the lack of a geomorphic model to guide monitors in documenting and interpreting change over time at impacted archaeological sites.

The RCMP monitoring efforts have recorded by fiscal year (October 1–September 30) both natural and visitor-related impacts to 285 sites within GRCA from 1992 to 1999. Since 1994, 55% of all monitored sites in the Grand Canyon have been impacted by some kind of channelization process. During FY 1998 alone, 37% of all recorded physical impacts to these sites were caused by active gully erosion; incipient thalweg development (keyed as "surface erosion" in RCMP reports) was noted in 25% of all observations. Changes in streams have become significant, as river-based streams are draining across archaeological features at 25% of monitored sites. Unfortunately, we could not determine from the Grand Canyon RCMP data when most of these streams breached the lowest alluvial deposits. Furthermore, many of these streams have become river-based since the completion of the dam (Leap et al. 2000), probably developing after 1976 (Hereford et al. 1993), infilling during the controlled flood in 1996 (Yeatts 1996), and then becoming river-based again.

An effort to prioritize sites for remedial action in FY 1999 (Leap et al. 1998) was recently undertaken to attempt to identify highest-risk sites. Neal (2000) could not determine precisely how the ranking process was developed or carried out, as either no consistent descriptive history of a given site is provided, or there are discrepancies in data or recommendations from year to year. We were able to determine that prioritization was based on present-day conditions, whether erosion appears "active," and whether archaeological materials and features are being exposed. The RCMP coding system appears to be the key to mitigating adverse effects to actively eroding sites. However, if we can help to refine RCMP's methods so that recorded data are more objective and quantifiable, justification for either preserving or excavating these sites would be strengthened. Since the Grand Canyon/Glen Canyon river corridor archaeological monitoring program could very well set the precedent for other NPS archaeological monitoring programs nationwide, it is critical to refine monitoring methods, decrease subjectivity, increase quantifiable parameters, and maintain consistency in annual data collection and management.

CHAPTER 2

METHODS

Kate S. Thompson, Andre R. Potochnik, Gary O'Brien, and Ron Ryel

This study pursued two separate lines of investigation that address erosion of cultural sites in sand terraces along the Colorado River in Grand Canyon National Park (GRCA). In the first part of the study we investigated three sets of hypotheses that have been developed by previous researchers; in the second part we sought to developed a predictive geomorphic model to identify archaeological areas where risk of gully erosion is high. Both parts of the study required a selection of study sites within those geomorphic reaches that contain high concentrations of archaeological sites. The study sites were identified in coordination with the River Corridor Management Program (RCMP) to ensure that catchment selections are closely related to nearby archaeology.

SELECTION OF STUDY SITES

Four reaches of Grand Canyon were found to contain most of the cultural sites that are on high sand terraces: Marble Canyon, Furnace Flats, the Aisles, and Western Grand Canyon (Figure 1.1). Within each of these reaches, catchments were identified that drain through culturally rich areas (Table 2.1). The main criterion for selection was that channels extend at least as far as the lower mesquite terrace (lmt) that was overtopped by the 300,000 cubic feet per second (cfs) flood of 1884. For the most part we also selected terrace-based streams so that they could be rated in the predictive geomorphic model and incorporated into future monitoring of cultural resources. Several catchments were chosen to represent end points in the rating system so that the predictive model could be calibrated. The highest-risk sites, such as Axehandle Cove, have the largest active arroyos, and the lowest risk-sites, such as those in the dune field at Nankoweap, have stable, swale-like channels.

Field work at these sites was conducted following procedures that were highly sensitive to cultural resources and to fragile desert soils. The concept of using the "minimum tool" to minimize the amount of human intrusion is important for preventing the creation of research-related trails and unnecessary human-induced erosion to archaeological sites.

TESTING THE HYPOTHESES

Three hypotheses describing the relationship between the emplacement of Glen Canyon Dam and erosion at archaeological sites along the river corridor were tested. The null hypothesis was examined by Hereford and others (1993), Lucchitta (1991), and Fairley and others (1993). The two alternate hypotheses tested were proposed by Hereford and Webb (1992) (referred to in this report as the climate-variation hypothesis) and by Hereford and colleagues (1993) (referred to in this report as the base-level hypothesis).

Table 2.1. Cultural Areas in Grand Canyon Containing Study Catchments

Reach	Area	River Mile/Side	No. of Catchments
Marble Canyon	Paria Cove	1.0 R	2
	Axehandle Cove	2.0 L	3
	Ten Mile Rock	10.0 R	1
	Soap Creek	11.2 R	3
	Willy's Grave	44.8 L	1
	Little Nankoweap	51.7-52.0 L	5
	Main Nankoweap	52.2-53.3 R	12
	Kwagunt Canyon	56.1 R	1
	60 Mile Canyon	59.7 R	2
Furnace Flats	Lava Canyon	65.3 L	2
	Palisades Creek	65.4-65.6 L	10
	Espejo Creek	66.9-67.0 L	3
	Comanche Creek	67.1-67.8 L	4
	Tanner Canyon	68.9-69.0 L	2
	Basalt Canyon	69.3 R	5
	Lower Tanner	69.6-70.3 L	6
	Upper Unkar	71.5-71.6 R	8
	Old Unkar Camp	72.2 R	1
	Lower Unkar	73.2 L	3
Aisles	122 Mile Canyon	121.9-122.0 R	4
	Owl Eyes	134.5-134.6 L	4
	Fishtail Canyon	139.0 R	1
	140 Mile	139.7 L	1
Western Grand	Saddle Horse	176.3 R	2
	Old Heli Pad	182.7 R	1
	186 Mile	186.2 R	1
	190 Mile	189.7 L	1
	194 Mile	194.4 L	1
	196 Mile	196.2 R	1
	201 Mile	201.2 R	5
	202 Mile	201.9 R	2
	Indian Canyon	206.5 R	2
	Arroyo Grande	207.7-207.8 L	6
	Granite Park	208.5-209.1 L	9
	Below Granite Park	209.5 R	3
	Fall Canyon	211.5 R	1
Total	**36**		**119**

The Null Hypothesis

H_0: Terrace erosion rates and gully erosion rates on the terraces have remained unchanged from pre-dam time to post-dam time.

Test 1: Determine when large gullies formed in Grand Canyon using air-photo interpretation

Hereford and colleagues (1993) initially assessed the timing of large gully (arroyo) development on river terraces within a seven-mile reach of eastern Grand Canyon (RM 65-72). They concluded that arroyo development was not present in that area in 1890, and that most of the larger arroyos were present in 1965 air photos. Incipient gullies in the Upper Unkar area were noted in 1973 and were well developed by 1984. Hereford and colleagues concluded that gully erosion began to intensify sometime after 1973, and RCMP monitors indicate that it is continuing (Leap et al. 2000).

We chose a subset of 23 catchments in 10 of our study areas to assess when gullies formed or when arroyos were rejuvenated in Grand Canyon. Using low-altitude air photos taken from 1965 to 1996, we developed a time sequence that depicts when a certain stage of gully incision occured at the sites listed in Table 2.2. The basis for catchment selection was whether they presently incise the full suite of pre-dam sand deposits (Figure 1.2). Present-day arroyos are typically box-like in cross-channel shape and are up to 1-2 m deep and 5 m wide. The degree of arroyo development in the pre-dam period is represented only by the 1965 air photos (1:6,000), as this is the earliest low-altitude photography available for the river corridor in Grand Canyon. A systematic assessment of all photos was limited, because photos were missing, areas were shadowed, or the overflight had been too high to see the area clearly. Furthermore, once an arroyo could be seen to have reached its present level of incision, subsequent photos of that feature were not examined.

Another approach to examining this hypothesis would involve an extensive search for archived oblique photos taken by river runners and researchers. Hereford and others (1993) found and republished only two such photos, taken by R. C. Euler in 1965, which illustrate intact terrace escarpments at Upper Unkar. They also published repeat photos taken in 1983 and 1991 that show progressively more dissected and eroded slopes. Hubbard (2000) also shows a 1965 Euler photo and a repeat photo taken in 1996 of the same slope but from a different angle. These photos show that a pristine slope containing a pueblo wall in 1965 had collapsed into a gully by 1996.

A complete historical photo analysis exceeds the scope of this study as originally proposed and is worthy of its own study and funding. Duane Hubbard (personal communication 1999) is presently using historical repeat photography in a study centered around archaeologic areas. Results of this project will no doubt contribute to our understanding of the timing of formation of arroyos and gullies. We investigated several photo collections at various archives, including the Museum of Northern Arizona, Northern Arizona University, and GRCA. Our investigations of over 1500 photos in these collections taken by La Rue, Kolb, Lampland, McCullough, Stone, and Belnap proved to be essentially fruitless for this particular test, as these photographers focused on subjects other than pristine hillslopes that contain archaeology.

Table 2.2. Photographic Assessment of Arroyo Development in Grand Canyon

Area	**Catchment**	**Date Photo Taken**							
		5/14 1965	6/16 1965	6/16 1973	7/11 1980	10/21 1980	10/21 1984	10/11 1992	4/6 1996
Soap Creek	A	NG	NA	PG	NA	NA	FG	NA	NA
	B	NG	NA	PG	NA	NA	FG	NA	NA
	C	NG	NA	PG	NA	NA	FG	NA	NA
Palisades Creek	H	PG*	NA	PG*	NA	NA	FG	NA	NA
Espejo Creek	A	NG	NA	NG	NA	FG	FG	NA	NA
	B	NG	NA	NG	NA	PG	FG	NA	NA
Comanche Creek	F	NG	NA	NG	FG	NA	FG	FG	NA
	H	NG	NA	NG	PG	PG	FG	FG	NA
Tanner Canyon	A	PG*	NA	PG*	FG	NA	FG	NA	NA
	B	PG*	NA	PG*	FG	NA	NA	NA	NA
Lower Tanner	A	NA	NG	NG	NG	NG	FG	NA	FG
	B	NA	NG	NG	NG	NG	PG	NA	PG
	C	NA	NG	NG	NG	NG	FG	NA	FG
Upper Unkar	D	NG	NA	NA	NG	NG	PG	FG	FG
	E	NG	NA	NA	NG	NG	PG	FG	FG
Lower Unkar	A	PG	NA	PG	PG	PG	PG	FG	NA
	B	PG	NA	PG	PG	PG	FG	NA	NA
	C	PG	NA	PG	PG	PG	FG	NA	NA
Arroyo Grande	A	PG	PG	PG	FG	NA	FG	NA	FG
	B	NG	NG	PG	PG	NA	FG	NA	FG
RM 209.5	A	NA	PG	PG	FG	NA	NA	NA	FG
	B	NA	PG	PG	FG	NA	NA	NA	FG
	C	NA	NG	PG	PG	FG	NA	NA	FG

NG = no gully present in terraces or stream is terrace-based on ap/sa terrace
PG = partial gully development or stream is terrace-based on mt or pda terraces
FG = full gully development or stream is terrace-based on 1983 sand or below
NA = no assessment – photos are not available, gullies not discernible on photo, or assessment not needed.

Test 2: Compare amount of gully erosion on terraces of a control section of river (Cataract Canyon) to that in Grand Canyon

In this test, we ask if gully density and activity in the Cataract Canyon control area and a similar geomorphic reach in Grand Canyon are different. The first step in making this comparison was to demonstrate that Cataract Canyon, a 15-mile section of the Colorado River that drains into Lake Powell (Figure 1.1), is a suitable analogue to the pre-dam setting of Grand Canyon. Cataract Canyon was chosen as potentially suitable as a control because in this area the geomorphic setting and climate are somewhat similar to those in Grand Canyon, but dams have relatively little influence on the natural hydrograph and sediment flux. We determined that the climate and physical setting of a study section in Cataract Canyon are comparable to conditions in the Furnace Flats reach in Grand Canyon (Figure 1.1), where 39% of our study catchments are located. Not only do the two areas lie in similar climatic zones, but the Colorado River carries through Cataract Canyon a similar pre-dam sediment load with an annual hydrograph approximating that of Grand Canyon (Van Steeter and Pitlick 1998). One difference is that many river recirculation zones in Cataract Canyon are formed below constrictions caused by landslides and rockfalls rather than by tributary side canyon debris fans. Nonetheless, river dynamics are similar to those found in Grand Canyon. Table 2.3 shows the similarities in the comparative data for the two areas.

Table 2.3. Comparison of Physical Characteristics of Cataract Canyon and the Furnace Flats Reach of Grand Canyon

Characteristic	**Cataract Canyon**	**Grand Canyon (Furnace Flats Reach)**
River gradient (m/km)	2.42	1.95
Reach length (km)	11	13
Elevation (m)	1158	807
Mean annual precipitation (mm)	220	233
Mean monsoon season temperature (C)	22.2	23.8
Mean monsoon season precipitation (mm)	86	97
Number of precipitation events exceeding 25 mm/day (1964–1995)	6	8
Percent of months in monsoon season receiving >50 mm precipitation	9.1	9.0
1957 flood stage* (cfs)	101,000	120,000

Note: Climate data used are from Moab, Utah, for Cataract Canyon and from Phantom Ranch for Grand Canyon (Western Regional Climate Center 1999).
*1957 figures represents a typical flood stage before closure of Glen Canyon Dam; GC gage at Lees Ferry and Cataract Canyon is the sum of flows recorded at Cisco and Green River.

The geologic strata of Cataract Canyon, like those in Grand Canyon, consist of Pennsylvanian and Permian resistant limestones and sandstones interbedded with softer shales, creating a cliff-bench topography. In both areas, the structural attitudes of strata are horizontal to gently inclined with minor faulting and folding (Huntoon, Billingsley, and Breed 1982). The geomorphic setting along the river in both canyons is similar in that periodic constrictions of the channel cause a pool-and-drop morphology. Constrictions are caused by side canyons producing tributary debris fans, talus slopes and rock falls reaching the edge of the riparian zone, or land slumps (Toreva blocks) reaching the river; the latter are more common in Cataract Canyon (R. H. Webb, personal communication 1998).

Since there is no published work on the alluvial history of Cataract Canyon, we conducted field investigations to develop relative ages, absolute ages, and correlation of river terraces for Cataract Canyon and Grand Canyon. Data collected on river terraces in Cataract Canyon included tree-ring samples, radiocarbon samples, sediment samples, height and width of terraces, diagnostic driftwood lines, diagnostic artifacts in driftwood piles, and vegetation community. Previous dendrochronological data from netleaf hackberry collected in Cataract Canyon were supplied to us by Alex McCord (personal field notes, unpublished), along with a publication of work in Grand Canyon by McCord and others (Salzer et al. 1996). This work, in conjunction with our tree-ring results, helped us correlate pre-dam flood deposits in Cataract and Grand canyons. We also correlated historical streamflow data for Cataract Canyon with the primary river flood events that formed terraces in both Cataract Canyon and Grand Canyon..

We then identified three study sites in Cataract Canyon that are geomorphically similar to three sites in Grand Canyon. The Cataract Canyon sites are Rapid 4, Cross Canyon, and Rapid 12. The Grand Canyon sites are Palisades Creek, Tanner Canyon, and Upper Unkar. Gully density and individual gully depths were measured to compare the degree of erosion at each site.

The Climate-Variation Hypothesis

H_1: Gully erosion on alluvial terraces associated with archaeology has increased from pre-dam time to post-dam time due to variation in precipitation patterns.

Test 1: Evaluate previous research on decadal-scale precipitation variations that may be responsible for increased erosion rates

Regional maps (Edwards and Batson 1990) indicate that the elevation of the Colorado Plateau averages more than 1200 m (3940 feet) above sea level, whereas the average elevation of the Basin and Range province in the Lake Mead area is less than 1200 m (3940 feet) above sea level. The regional elevation gradients from the high plateaus to the low deserts strongly influence precipitation patterns across the region.

Precipitation in this region is characterized by two wet seasons, one produced by frontal storm systems in the winter and the other by monsoon systems in the late summer (Hereford and Webb 1992; Hansen and Schwarz 1981). Frontal systems originate in the Pacific Ocean and track eastward across the region. These systems tend to be more pervasive toward the north, dissipating in energy toward the south. The summer systems originate from the Gulf of Mexico or the Sea of Cortez and track northward into the southwestern United States before circulating eastward into the Great Plains (Griffiths, Webb, and Melis 1996). Some researchers have proposed anomalous wet periods of both warm season and winter season precipitation from the late 1970s through the 1990s have accelerated gully erosion of alluvial terraces (Hereford et al. 1993; Webb, Griffiths, and Melis 2000).

Several researchers have suggested that warm-season rainfall is the primary cause of fluvial erosion, sediment transport, and land surface change in the region (Graf, Webb, and Hereford 1991; Hereford 1989; Melis et al. 1996; Webb 1985). Warm-season rainfall generally occurs between June 15 and October 15 (Hereford and Webb 1992) and is typically the result of isolated thunderstorms of the southwestern monsoon or, less frequently, of dissipating tropical cyclones or cutoff low pressure systems that produce widespread rainfall. In this paper, we use the term "monsoon season" precipitation to refer to all warm-season precipitation from July 1 to October 31, regardless of the type of storm system.

A relatively few, very large debris flows from tributary canyons have been attributed to winter-season rainfall from large frontal storm systems (Cooley et al. 1977; Melis et al. 1994; Webb et al. 2000). These storms may be intense and are commonly of longer duration than warm season storms. Very intense localized convective storm systems and high monthly precipitation have been related to the triggering of debris flows and tributary flooding in Grand Canyon. High seasonal precipitation, on the other hand, does not correlate well with large tributary floods in Grand Canyon (Griffiths et al. 1996; Melis et al. 1996, Webb et al. 2000).

For this test we examined previous research on variation in twentieth-century precipitation patterns across the Grand Canyon and the southern Colorado Plateau to determine if there is a cause-and-effect relationship between precipitation and arroyo cutting.

Test 2: Investigate variations in monsoon season rainfall at equivalent time periods before and after closure of Glen Canyon Dam

To assess variation in monsoon season rainfall, we needed to pool as much data as possible from weather stations throughout the southern Colorado Plateau. We then isolated local variation in seasonal precipitation by subdividing the path of the Colorado River through the southwestern Colorado Plateau into four distinctive topographic regions: Lower Colorado River, Western Grand Canyon, Kaibab-Mogollon Plateaus, and Lake Powell–Canyonlands (Figure 2.1). We designated each region by its predominant physiographic feature and used these names only for the purpose of regional climate assessment in this report. The Lower Colorado River region west-southwest of Grand Canyon lies mostly below 900 m (2950 feet) elevation. Winter-front moisture from the Pacific Ocean generally passes over this low desert region south and west of the Colorado Plateau. Weather stations in this region record precipitation ranging from 120 to 180 mm (5-7 inches) per year (Western Regional Climate Center [WRCC] 1999). The Western Grand Canyon region lies between Lake Mead and Kanab Creek in Grand Canyon. It is a series of high plateaus that progressively ascend in elevation from 600 to 1800 m (1970-5900 feet) over a broad region that receives 200-400 mm (8-16 inches) of mean annual precipitation (WRCC 1999).

Figure 2.1. General climatic zones of the southwestern Colorado Plateau based on physiography and elevation.

From Kanab Creek to the Little Colorado River, the plateaus rise even more sharply to form the Kaibab-Mogollon (K-M) Plateaus. This region is part of a broadly arcuate topographic high that extends from the Mogollon Rim of central Arizona northward through the San Francisco volcanic field into the Coconino and Kaibab plateaus of northern Arizona. The crest of the K-M plateaus varies in elevation from 1800 to 2500 m (5900-8200 feet), with the Colorado River cutting through its midsection at about 750 m (2460 feet) elevation. The K-M plateaus area receives 300-600 mm (12-24 inches) of precipitation per year, while the mean annual precipitation at Phantom Ranch averages 230 mm (9 inches) (WRCC 1999).

The Lake Powell–Canyonlands region lies in the rain shadow of the Kaibab uplift and extends far to the northeast from the Little Colorado River to Moab, Utah. Toward the northeast, the K-M highland drops over 1000 m (3280 feet) in elevation to form the semiarid Marble Platform and Lake Powell region. This region lies between 950 and 1500 m (3115-4920 feet) in elevation and receives between 125 and 250 mm (5-10 inches) of precipitation annually (WRCC 1999).

We assessed climate records to determine whether there are any obvious variations in monsoon season precipitation in the post-dam period. Weather stations were identified with records that include the period from 1932 to 1995, so that 32-year periods pre- and post-dam could be compared. Weather stations included in this analysis lie within a broad region that parallels the river corridor from western Colorado to western Arizona (Figure 2.2). For this analysis we used two parameters of monsoon season rainfall: (1) large daily precipitation events and (2) large monthly volumes of precipitation.

Figure 2.2. Location of weather stations from which 64-year daily precipitation data were compiled.

Using available precipitation data, we counted the number of precipitation events greater than 25 mm/day for each of the two 32-year periods. We did the same for the number of months in the monsoon season with total precipitation above 50 mm. These data are summarized in Table 2.4. Monthly precipitation is given as percent values because of the difference in the number of missing values for the two periods. One important weather station, Phantom Ranch, has records only from 1948. In this case, figures for the shorter pre-dam period are multiplied by 2 to extrapolate to the 32-year pre-dam period, and these data should be regarded as approximations.

Table 2.4. Summary of Data Used for Investigating Precipitation Changes Before and After Emplacement of Glen Canyon Dam

Weather Station	Period Analyzed	Percent of Records Missing	Elevation (m)	Number of Days with > 25 mm Precipitation		Percent of Months with > 50 mm Precipitation	
				1932-1963	1964-1995	1932-1963	1964-1995
Lower Colorado River							
Boulder City, NV	1932-1998	2.27%	767.8	12	23	3.23%	5.93%
Parker, AZ	1932-1998	0.00%	128	10	10	3.31%	4.03%
Western Grand Canyon							
Zion National Park, UT	1932-1998	0.05%	1234	15	17	15.32%	20.97%
Seligman, AZ	1932-1998	0.06%	1600	16	19	21.70%	27.87%
Kingman, AZ	1932-1993	2.58%	1051	44	26	13.04%	14.04%
K-M Plateaus							
Escalante, UT	1932-1998	0.10%	1770	25	11	25.86%	14.52%
Phantom Ranch, AZ*	1948-1998	6.81%	783.1	14	8	12.50%	9.01%
Grand Canyon, AZ	1932-1998	3.90%	2096	23	40	32.77%	34.15%
Fort Valley, AZ	1932-1998	0.07%	2240	25	38	49.19%	52.42%
Lake Powell-Canyonlands							
Grand Junction, CO	1932-1998	0.08%	1475	4	4	9.68%	6.45%
Moab, UT	1932-1998	3.08%	1225	14	12	12.82%	9.09%
Bluff, UT	1932-1998	0.08%	1316	11	5	8.87%	7.26%
Lees Ferry, AZ	1932-1995	9.41%	978.1	11	9	5.61%	5.26%

*Phantom Ranch record is for the 16-year period before the dam and was standardized to the 32-year period by multiplying by 2.

The Base-Level Hypothesis

H_2: *Gully erosion on alluvial terraces associated with archaeology has increased from pre-dam time to post-dam time due to base-level effects.*

Test 1: Report on rebuilding of sand bars that buttress pre-dam terraces and infill gullies in Grand Canyon and in Cataract Canyon

In Grand Canyon, previous researchers reported on sand-bar rebuilding and gully infilling associated with archaeological sites (Burchett, Coder, and Hubbard1996; Yeatts 1996, 1998). Most of this work, conducted by repeat topographic surveys and repeat photography, centers around the experimental test flood of 1996 and the resilience of these sand bars following that time.

Using the concepts employed by Yeatts (1996), we conducted topographic mapping in Cataract Canyon to show volume change in three areas prior to and following the annual spring flood of 1999. The three areas—Rapid 4 (RM 211.3L), Cross Canyon (RM 208.4L), and Rapid 12 (RM 206.7L)— were selected from an 8-mile survey reach of Cataract Canyon that is closely analogous to the Furnace Flats reach in Grand Canyon. These particular areas were selected because they have a complete terrace sequence and river- and/or terrace-based streams within a small area. Stream profiles and mouths were surveyed before and after the annual flood to detect any loss or gain in volume of sediment. This comparison provided quantitative evidence of sand bar dynamics in an undammed system and in an equivalent dammed system.

We rephotographed these three sites and others in Cataract Canyon for degree of gullying and flood-sand renewal for the two-year period of study. These photos can be compared to photo documentation of sites by RCMP monitors in Grand Canyon following the 1996 BHBF, providing a simple means of annotating changes in areas representing pre-dam and post-dam conditions.

We also investigated historical photo archives to show the relative elevation and extent of sand-bar rebuilding around archaeological areas in pre-dam time in comparison to conditions today. The photo archives used for Test 1 of the null hypothesis were used for this test as well.

Test 2: Assess catchment and river processes at each study site in Grand Canyon

The base-level hypothesis was further tested by conducting field work at each of the sites listed in Table 2.1. We identified all of the alluvial terraces present, using characteristics and syntax described by Hereford and others (1993) (Figure 1.2).

Specifically, we noted at each site characteristics of the process of channel integration with the river. Using a deductive approach, we could eliminate processes that were completely unrelated to the dam and its operations and assign points accordingly (Table 2.5). The geometry of the river was recorded, along with any evidence of sediment renewal in the time directly preceding the dam and in post-dam time. Sediment renewal refers to freshly deposited river sand or active eolian sand that replenishes the mouths of streams and interrupts channel downcutting or helps maintain sand bar elevation. We recorded whether gullies drain toward a recirculation zone (upper pool, separation, or reattachment bar), point bar, or cutbank (channel margin bar). Thus, we recorded presence of the pre-dam alluvium (pda), 1983 flood sand, and any active eolian sand derived from these deposits. Presence or absence of these deposits indicates how they may have blocked or slowed downslope channel evolution in the time just before and after emplacement of the dam. Collectively, these observations provide clues to the validity of the base-level hypothesis. We then rated the strength (or weakness) of the base-level hypothesis at each site, using the values in Table 2.5, according to the documented processes at work. If a particular geomorphic process or sand deposit was present, we assigned that characteristic a value of 1. Scores for each site were totaled and evaluated for base-level control properties.

Table 2.5. Scores Assigned to the Presence of Specific Geologic Units or Geomorphic Processes

Description	**Score**
Geomorphic Process	
gully not caused by side-canyon erosion	1.00
bank retreat at river level not caused by natural geometry of river	1.00
no evidence of pre-dam arroyo cutting (determined from 1965 air photos)	1.00
Sandy Deposit Present	
pre-dam alluvium and 1983	1.00
eolian dune (reworking of flood sand)	1.00
Maximum Score Possible	**5.00**

Note: The Maximum Score is used to test the strength of the base-level hypothesis.

DEVELOPMENT OF A PREDICTIVE GEOMORPHIC MODEL

A geomorphic model was developed to explain processes that cause erosion of high sand terraces. Specifically, the model was designed to predict the relative vulnerability of the terrace sequence to gully erosion, because these terraces lie in the runoff path of local catchments. The model can be used by resource managers and monitoring teams to effectively assess and mitigate adverse impacts to cultural materials that would otherwise be lost to erosion. It also identifies the highest-risk sites where data recovery of archaeological materials should be a priority.

The Small-Catchment Geomorphic System in the Grand Canyon

Geomorphic settings in which cultural sites exist can be characterized by underlying rocky material, which reflects the nature of the local hillslope or stream environment. The configuration of the river corridor near river level is controlled by its resistance to erosion. Easily erodible shales (e.g., Moenkopi Formation, Hermit Formation, Dox Formation, Hakatai Formation, and Bright Angel Shale) tend to form wider and more gently sloped sections in the river corridor. In addition, erodibility is increased in fault zones, where the rock is often highly fractured. A wider river corridor with a more gentle slope has greater accommodation space for the deposition and preservation of river terraces through time. The opposite is true for the harder rock formations that form the narrow and steep-walled reaches of the corridor (e.g., the Supai Gorge, Granite Gorges, and Muav Gorge) (Schmidt and Graf 1990).

The shape and size of tributary debris fans largely control the distribution, thickness, and extent of sandy river terraces in the corridor. Gravel debris fans are formed by sediment-laden floods and debris flows that episodically flow from the tributary canyons. A debris fan causes a narrowing of the river that is followed by a wider area with a recirculation zone (eddy). Within these wider areas, sand is deposited in the slower currents (Schmidt 1990). The size, shape, and composition of these debris fans are functions of the rock type, catchment size, and slope of the tributary canyons (Potochnik and Reynolds 1990). These variations in debris-fan complexes create different response mechanisms in small catchments trying to reach equilibrium with the post-dam floodplain of the river. Therefore, we sub-categorized fan complex settings, from largest to smallest, as tributary plain, alluvial fan, and debris lobe. A number of cultural sites lie at the base of talus slopes, in alluvium at the fringe of or away from the tributary fan complex; this context is termed the talus-slope setting. Finally, many cultural sites in our study are in a dune field setting, in which channels have formed. Although these areas are often associated with tributary fan complexes, eolian processes are the dominant mechanisms that control the stream environment. The five unique geomorphic settings are illustrated in Figure 2.3. Many catchments are influenced by more than one of these settings, but we feel that each can be categorized on the basis of the primary setting present.

To fully understand processes at each of these geomorphic settings, we established type geomorphic settings with associated catchments established for detailed study. Small-scale topographic maps were created by Horizons, Inc., for areas representing each of the five geomorphic settings. These maps were produced by computerized photogrammetric technology from 1998 aerial photography at 0.25-m contour intervals. Individual boulders 0.5-1.0 m in size are clearly visible features on these maps, as are gullies and large headcuts with measurable widths and depths. We sought map bases with a large enough scale to plot details within the channel, such as areas of channel roughness, nickpoint locations, and stream cross sections. Other data gathered for these sites include soil infiltration rates, grain-size distributions (R. Hereford, written communication1998), surficial geology (Hereford 1996; Hereford, Burke, and Thompson 1998), and location of archaeological sites.

Figure 2.3. Schematic illustration of the five geomorphic settings along the Colorado River. Terrace-based streams drain to or above the 1983 flood sand; river-based streams cut through the 1983 sand.

The areas selected for this detailed work, with their respective catchments (designated by letters), are:

- Alluvial fan setting – Nankoweap (catchments O, Q)
- Tributary plain setting – Palisades (catchments H, H')
- Talus slope setting – Upper Unkar (catchments A, E)
- Debris lobe setting – 122 Mile (catchments B, C)
- Dune field setting – Lower Tanner (catchments A, C)

Data collected at these sites were archived in ArcInfo; thematic data are shown as layers on the baseline topographic maps (Plates 2-6, in folder at end of document). Characteristics of each geomorphic setting and its catchments are described in Chapter 3.

U.S. Geological Survey (USGS) maps (Burke and Hereford 1999; Hereford 1996; Hereford, Burke, and Thompson 1998, 2000a, 2000b) with their comprehensive and detailed descriptions served as an invaluable resource for this study and substantially increased the efficiency of office and field work. These maps were useful for quickly assessing the detailed geomorphology of field sites, understanding geomorphic units and their interrelationships, and conceptualizing a framework in which to do detailed geomorphic analyses.

Topography in four of the five type-setting maps was tested for accuracy by overlaying available digital versions of the USGS map topography produced by the Hereford group. Further accuracy checking included comparison of random measurements of stream cross sections taken in the field with computer-generated measurements of the same cross sections from the maps. However, we found the scale of USGS maps produced by Hereford and others too small for documenting subtle variations in landforms and their change through time. Furthermore, existing GIS and archaeological site maps produced by Grand Canyon Environmental Studies (GCES) and GCMRC that include our sites did not have the detailed coverage or accuracy needed to complete our study, since they were not intended to cover the upper talus/bedrock area and lower terrace areas by the river.

Developing the Matrix of Geomorphic Conditions

During the inventory of study sites, we identified geomorphic factors that clearly influence catchment and river processes. These factors are categorized as either intrinsic or extrinsic to catchment processes (Schumm 1977). Intrinsic factors control rainfall-induced runoff within the catchment area and the terrace sequence that lies below. Extrinsic factors include processes related to restoration or erosion outside of internal catchment processes. Several factors measured in the field were later found to be unnecessary for development of the mathematical model but were useful for the field-rating model and site descriptions.

Processes operating intrinsically within the catchment can be further divided into driving and resisting factors (Bull 1991). The upper catchment or talus/bedrock portion contributes runoff and funnels it onto the terrace sequence, which absorbs this energy (Figure 2.4). This relationship can be conceptualized simply as a funnel perched above a sponge. When water is poured into the funnel, the energy becomes concentrated as it is delivered onto the sponge, which then dissipates the energy. When the sponge has absorbed the maximum volume of water it can contain, runoff occurs. We employ this concept in formulating the mathematical model, which is discussed in the next section of this chapter.

Intrinsic Factors of Catchments

Factors driving erosion occur within the bedrock and gravel region of the catchment, upslope of the terrace sequence. These factors are measured as follows:

Driving Factors (upper catchment)

- Drainage Area — total drainage basin area in square meters measured on air photos and in field by survey equipment; subdivided into bedrock, gravel, and sand portions
- Stream Length — total length in meters of main thalweg measured on air photos and in field by survey equipment

Figure 2.4. Schematic illustration showing process of channel integration with the river. The upper catchment acts as a funnel that delivers water onto the terrace "sponge." Alluvial fan progradation across the terrace accommodates the channel in reaching the river.

- Runoff Efficiency — coefficient based on weighted mean of area containing three types of lithologies (bedrock, gravel, sand)
- Upper Catchment Length — distance in meters from highest point in upper catchment to uppermost sand terrace
- Catchment Relief — total relief in meters from highest point in catchment to uppermost sand terrace
- Slope of Bedrock/Talus Portion — degree of slope as measured with a clinometer; measurement taken from base of talus to top of catchment in bedrock
- Shale Factor — percent area of shale covering upper catchment; determined from air photo analysis

Resisting Factors (occur in terrace portion of catchments)

- Ground Cover (vegetative and non-vegetative) — percent ground cover measured by the point-intercept method along a transect and categorized according to vegetation/soil type: (1) woody, (2) herbaceous, (3) organic detritus (includes cryptobiotic soil, deadfall, driftwood, leaf and grass litter), (4) rock, (5) bare ground

- Grain Size Distribution — field assessment of grain sizes (U.S. Department of Agriculture hand texture method); also identified whether sediments of eolian or fluvial origin
- Permeability — infiltration rates in inches per second measured with Gwelph permeameter at each of the "Type Catchment" sites
- Width — width of terrace in meters from bottom of riser to back of tread
- Height — height of terrace in meters from bottom of riser to back of tread
- Sand Depth — depth of terrace in meters as estimated from cross section in nearby side canyon or arroyo
- Number of Terraces — number of terraces a channel must cross to reach the river; counted from base of upper catchment to the 1996 stage height

Extrinsic Factors of Catchments

Extrinsic factors drive erosion and restorative factors outside of catchment internal processes. They are measured or assessed as follows:

- Human Mitigation — presence of checkdams or revegetation
- Eolian Infilling — percent of active windblown sand over area
- Flood Flow Infilling — presence of 1983 and 1996 flood sands
- Human Impact — qualitative assessment of degree of trailing, categorized as: (1) slight (footprints only), (2) moderate (trail intersects channel), (3) severe (stream established downslope along a trail)
- Side Canyon Overflow — presence of side canyon overflow that partly forms channel

Field data were collected during four river trips through Grand Canyon and four river trips through Cataract Canyon between February 1998 and August 1999. Since field crews were dispatched to collect data, the protocols defined above were established to assure consistency in data collection. Customized field data sheets (see Appendix A) were issued for crew members to ensure complete data gathering for each catchment. All data were archived into Access® to streamline data management. Data were manipulated in both Access® and Excel® to consolidate and graph results.

It should be noted that none of these measurements were repeated because of the short duration of this project. However, all measurements were systematically collected and were carefully recorded so that repeat data collection may be carried out in the future. A clear understanding of geomorphic processes is an essential prerequisite for the establishment of an effective long-term monitoring program that will provide significant results through time-series analyses.

STEPS IN ASSEMBLING THE PREDICTIVE MODEL

The second main objective of this study was to develop a quantitative model that would predict the vulnerability of high terraces to gully erosion from local catchments. We explored four separate approaches and chose a process-based mathematical model as the best method.

Statistical Model Approach

The purpose of the model is to predict which areas are most vulnerable to erosion and which will erode first. Our first approach was to apply Principle Component, Multiple Regression, and Cluster analyses to draw out relationships among variables. Moreover, we tried through these multivariate analyses to reduce the number of measured variables and identify those that are most discriminating. We were hoping that patterns in the data could be identified through statistical relations among intrinsic geomorphic parameters. Unfortunately, we could not find consistent patterns relating these parameters to the actual degradation of study sites.

This failure did not reflect a lack of causal relationships, but resulted from the discrete nature of major erosion events induced by rainfall. Catchment basin characteristics certainly relate to vulnerability (Leopold and Maddock 1953; Schumm 1977); however all sites do not equally show that vulnerability if they have not yet received the random high-rainfall event that will cut a large channel. Some sites have received such events and thus exhibit high erosion characteristics. Others with similar physical properties show little channel degradation, probably because they have not received the same type of large rainfall events. Multivariate analyses will thus fail to show relationships, because the entire range of erosion conditions is possible with the same physical characteristics. This confounding problem resulted in the development of a more mechanistically based model with response frequencies as an indicator of the model.

Sediment yield, which is the weight or volume of sediment eroded from a unit area, was also investigated for its usefulness in modeling gully erosion in terraces. Several empirical equations have been developed to estimate sediment yield, but these models, such as those developed by Fournier (1960) and Flaxman (1972), generally relate sediment yield to climate and watershed variables. Since it was impossible to measure rainfall at each Grand Canyon site, we felt that a customized approach would be more useful. Moreover, these models are designed for large catchments; sediment yield is extremely difficult to measure in the small-catchment environment of our study sites, and figures obtained would falsely reflect the rate of gully erosion. Critical variables such as those indicating rainfall/runoff relations, watershed morphometry, sediment grain size, and vegetation are the focus of our conceptual process model.

We also explored use of a field-rating model for consistently recording observations on each site and providing qualitative assessments of site vulnerability. The field-rating model uses geomorphic parameters (identified in Table 2.6) that were considered to be the most critical in assessing vulnerability in the field (Leopold and Maddock 1953; Schumm 1977). Other standard methods for

Table 2.6. Point Scale for Parameters within the Catchment

Bedrock/Talus Portion			
Score	***Catchment Area (m^2)***	***Slope of Talus/Bedrock (degrees)***	***Slope Aspect (degrees)***
0			
1	< 200	0-10	0-44
2	200-700	11-20	44-89, 315-360
3	700-5000	21-30	90-134, 270-314
4	5000–20,000	31-40	135-179, 225-269
5	20,000–100,000	41-50	180-224
6	> 100,000	51-60	
7		61-70	
8		71-80	
9		> 80	

Sandy Portion					
Score	***Slope of Sandy Terraces (percent)***	***Width of Sandy Terraces (m)***	***Bare Ground (percent)***	***Number of Terrace Levels***	***Human Trailing***
0		> 250	< 9	6	none
1	< 6	201-250		5	slight
2	6-10	151-200	9-20	4	moderate
3	11-15	101-150		3	severe
4	16-20	50-100	21-40	1-2	
5	21-25	<50			
6	26-30		41-60		
7	> 30				

Note: Quantitative breaks in data follow standard method of rating sediment yield (PSIAC rating [PSIAC 1968]) or are statistically derived from frequency distributions.

estimating soil erosion (Universal Soil Loss Equation) or sediment yield (PSIAC Rating [Pacific Southwest Inter-agency Committee 1968]) use these same parameters, with the exception of "number of terrace levels." Based on empirical evidence in Grand Canyon, we determined that the stepped sequence helps to slow and dissipate stream power and that a higher number of terraces therefore increases resistance to erosion.

While this method helped us to identify high-risk sites in the field, it did not rank sites of low to medium risk very effectively. Moreover, poor correlation was found when plotting the total vulnerability rating against actual degradation of the ap terrace (see Plate 1 for terrace descriptions). Therefore, we investigated a mathematical model that focused primarily on process.

Mathematical Model Approach

We developed a mathematical model using both Grand Canyon and Cataract Canyon data. The model is based on the concept of the upper catchment acting as a funnel for discharging water onto the terrace sequence below, with the terrace sequence acting as a sponge to absorb water and dissipate stream power (Bull 1991) (Figure 2.4). We used simple hydrologic equations to derive the vulnerability of terraces for each site in developing this process-based model.

For erosion-driving factors, we evaluated total runoff volume (Q) and peak discharge (Qp) from a hypothetical storm of 25 mm (1 inch)/hour to determine which of these factors is more accurate in representing the erosion-driving forces of a storm event. This event was chosen based on previous research on debris flow initiation (Griffiths, Webb, and Melis 1996). We assume that when a terrace becomes saturated with water and can no longer behave like a sponge, excess runoff induces gully cutting. Thus, the resistance of the terrace is fundamentally a function of its volume and permeability (diffusion capacity).

The volume of a terrace is assumed to be laterally infinite. Therefore, the critical dimension of a terrace's ability to absorb water is the shortest distance water must travel to reach the terrace riser, which we call terrace width (Wt). The other critical dimension is the thickness of the sand terrace above its rocky base, which we call terrace depth (Dt). In our model, cross-sectional area of a terrace (Axt) is the primary measure of a terrace's resistance to erosion, where:

$$Axt = Wt \times Dt \qquad \text{(equation 1)}$$

Other workers have suggested that a rainfall event of 25 mm/hour initiates debris and stream flows in tributary side canyons (Melis et al. 1996). Storm systems of this type are assumed to be the same ones that cause severe erosion of terrace-based catchments (Hereford et al. 1993). For simplification of modeling, we assume unsaturated conditions and do not include possible antecedent conditions of partial soil saturation. We therefore assume that lateral diffusion forces, which are inherent in saturated conditions (Fetter 1980), are negligible compared to downward gravitational forces, which are dominant in unsaturated conditions.

In our model, the upper gravel-bedrock portion of the catchment delivers a flow event of 25 mm/hour to the terrace portion, which we assume to be unincised for simplicity of modeling. Essentially, we are modeling the balance between the erosion-driving stream power of water in the upper catchment and the diffusion capacity of terraces below, referred to as the geomorphic threshold (Schumm 1977). This basic part of the model, which we address as Model 1, determines a site's vulnerability to gully incision. Other variables unique to each site, incorporated into the basic model as Model 2, help refine the vulnerability index of Model 1.

Model 1

First, Model 1 subjects the uppermost sandy terrace to total runoff volume (Q) from the hypothetical storm event. The vulnerability of the terrace (Qvul) is expressed as a percentage of the Q ratio:

Q vul = 100 (Q ratio/maximum Q ratio), (equation 2)

where Q ratio is a function of runoff from the upper catchment compared to resistance of the terrace below. The Q ratio in equation (2) is expressed as:

Q ratio = ln Q / ln Axt (equation 3)

Equation (3) simply normalizes the Q ratio for ease of graphing. The value Q is calculated using a modification of Fetter's (1980) Rational Equation and is expressed as:

Q = (I) (At) (C), (equation 4)

where Q = total volume of runoff (m3)
I = total rainfall (m)
At = total catchment area (m^2)
C = runoff coefficient

The value for C in equation (4) varies with three typical geologic surfaces (bedrock = 0.85, gravel = 0.35, and sand = 0.01 [American Society of Civil Engineers 1970]). It is calculated by the following equation:

C = (Ab * 0.85) + (Ag * 0.35) + (As * 0.10)/At, (equation 5)

where Ab = bedrock catchment area (m^2)
Ag = gravel/talus catchment area (m^2)
As = sand catchment area (m^2)

Next, Model 1 subjects the uppermost terrace to peak flow discharge, Qp (m^3sec^{-1}), from the hypothetical runoff event. We determine this terrace vulnerability (Qp vul) according to the equation:

Qp vul = 100 (Qp ratio/maximum Qp ratio), (equation 6)

where, similar to the terms of equation (2), Qp ratio is a function of peak flow discharge from the upper catchment compared to resistance of the terrace below. The Qp ratio in equation (6) is expressed as:

Qp ratio = ln Qp / ln Axt (equation 7)

Qp is derived from the following equation (McCuen 1982, in Western Water Consultants, Inc., 1992):

Qp = 484 * Q/(0.6665 * Tc), (equation 8)

where Q is the total runoff volume in mi^2-in and Tc is the time of concentration (the time it takes a particle of water in the most distant part of the basin to reach the outlet) in hours. Tc is expressed as:

$Tc = (Ls/0.3047)^{1.15} / 7700 * (H/0.3047)^{0.385}$, (equation 9)

where Ls is the length in meters of the main stream of the basin and H is the relief in meters between the most distant drainage divide and the outlet (Fetter 1980).

Model 2

From our field work at type geomorphic settings (Plates 2-6), we can generally distinguish pre-dam and post-dam sandy deposits. Based on grain-size research (R. Hereford, written communication 1998), we can assume that all pre-dam river terraces are composed of poorly sorted fluvial sand (silty fine sand) and have relatively uniform permeability (mean K = 0.005) (Table 2.7) compared to post-dam river terraces, which are composed of well-sorted fine sand (mean K = 0.05). This comparison illustrates an order-of-magnitude difference between the two main types of sediment. Furthermore, permeability of eolian deposits (mean K = 0.03) roughly mimics that of post-dam sand. Therefore, we lump post-dam and eolian deposits together when assessing their ability to absorb water.

Table 2.7. Infiltration Rates of Pre-dam, 1983, and Eolian Sand Deposits

Geomorphic Feature	Hydraulic Conductivity K (× 10-3 cm/sec)		
	Mean	Range	Number
Talus	50.0	2.0-191.0	5
sa Terrace/Alluvial	6.0	5.0-7.0	3
ap Terrace	5.0	1.0-10.0	5
1983 terrace	50.0	1.0-97.0	5
Eolian sand	32.0	11.0-68.0	3
Gravel*	370.0	N/A	N/A
Kaolinite (clay)*	0.0007	N/A	N/A

*Not measured in the field; values from Davis and DeWiest (1996).

Four geomorphic variables within terraces are also incorporated into the model (Figure 2.5). Two of these variables reduce the resilience of the terrace "sponge," whereas the other two increase it. The sum of these variables, which modifies the diffusion capacity of terraces, is stated as follows:

$$TF = SF + WF + HF + EF, \text{ and } -0.5 < TF < 0.5 \qquad \text{(equation 10)}$$

The shale factor (SF) is a function of shale comprising part of the upper catchment. This factor decreases permeability of water into the terrace by depositing clay and providing material to build alluvial fans across the terrace surface (Griffiths, Webb, and Melis 1996). SF is derived from the equation:

$$\text{if } [(\ln(As + 1)/ \ln(Lt + 1)] / (max) * 100 > 10,$$
$$\text{then } SF = -0.5; \text{ otherwise } SF = 0.0 \qquad \text{(equation 11)}$$

The numeric values representing how much SF and other factors contribute to TF were estimated in the field.

In equation (11), As = the upper catchment area composed of shale in square meters, and max = the maximum value of $[\ln(As + 1)/\ln(Lt + 1)]$.

The woody vegetation factor (WF) decreases diffusion of water into the terrace by increasing piping and seepage erosion along roots (Parker and Higgins 1990). It is calculated as follows:

$$WF = (\text{woody veg}) * -0.5, \qquad \text{(equation 12)}$$

where woody veg is the fraction of woody vegetation to terrace width (both in meters).

Figure 2.5. Flow chart showing inter-relationships of geomorphic factors and model development.

The herbaceous vegetation factor (HF) accounts for ground coverage of cryptobiotic soil, grasses, forbs, and organic matter. It increases diffusion of the terrace "sponge" (Schumm 1977) according to the equation:

$$HF = (\text{herb veg}) * 0.25, \qquad \text{(equation 13)}$$

where herb veg is the fraction of herbaceous ground cover to terrace width (both in meters).

The eolian factor (EF) accounts for reworking and sorting of sand by eolian and river processes. This factor increases permeability and diffusion of water into the terrace (Pye and Tsoar 1990) by winnowing out the silt and clay fraction from the sand. If the geologic description of a terrace is eolian or 1983 sand, then:

$$EF = 0.5; \text{ otherwise } EF = 0.0 \qquad \text{(equation14)}$$

Taking these four factors (equations 11–14) into consideration, the raw vulnerability quotient (Vr) of any individual terrace to erosion is independent of its position in a terrace sequence. It is as if the individual terrace were placed at the base of the catchment area where it would receive the full force of the runoff. This condition can be expressed as:

$$Vr = \ln(Q \text{ or } Qp)/\ln[Axt * (1 + TF)] \qquad \text{(equation 15)}$$

For ease of graphing, values for Vr are normalized and subsequently referred to as the final vulnerability quotient for individual terraces (FVi), expressed as:

$$FVi = 100 * Vr / \max(Vr), \qquad \text{(equation16)}$$

where max(Vr) = maximum Vr for all upper terraces using Model 1.

In most cases, an individual terrace is located below another terrace, which modifies its vulnerability quotient. A cumulative vulnerability quotient (FVC) was calculated for each terrace in the sequence as the product of its individual vulnerability quotient (Fvi) and the cumulative vulnerability from the previous terrace (FVC_{i-1}):

$$FVC_i = (FV_i \times FVC_{i-1})/100 \qquad \text{(equation 17)}$$

We obtained average vulnerability for each catchment by calculating the mean of all terraces (FVCi) per catchment (listed with Site Descriptions in Appendix B).

The mathematical model includes factors that are intrinsic to the rainfall-runoff process and its effects on a pristine terrace sequence. The model does not include extrinsic factors that, on a case-by-case basis, may strongly dictate the vulnerability of the terrace sequence at a site. Five factors, evaluated for each site, act to modify some of the predicted vulnerabilities from the mathematical model: (a) human impact, (b) side canyon overflow, (c) climate gradient, (d) (river sand renewal, and (e) eolian processes. These data are summarized in the Site Descriptions (Appendix B).

DEVELOPMENT OF THE CLIMATE PARAMETER FOR THE GEOMORPHIC MODEL

To detect a climate gradient as it pertains to our study area, we analyzed warm-season (summer monsoon, July-October) precipitation data specifically at river-level weather stations throughout the Colorado River corridor. The analysis extends to the fringe of the corridor that receives monsoon-season precipitation, from Moab, Utah, to Parker, Arizona (Hereford and Webb 1992; WRCC 1999). Analyzing only stations at river level eliminated local orographic effects on precipitation trends, because higher-elevation weather stations are not reliable indicators of precipitation patterns along the river (Melis et al. 1996). Data were analyzed for post-dam time, so that a climate gradient is consistent with the post-dam era in its application to the final vulnerability index. The data are summarized in Table 2.8 according to mean annual precipitation, mean precipitation for the monsoon season (July-October), mean precipitation for the peak month in the monsoon season, and number of days exceeding 25 mm (1 inch) of precipitation for the monsoon season. The data are concerned primarily with warm-season rainfall, because many arroyo-cutting episodes occur during that time (Hereford and Webb 1992). Table 2.8 summarizes the results of the climate parameter, which are discussed in Chapter 3.

Table 2.8. Summary of Precipitation Data from River-Level Stations for Thirty-two Years Following Emplacement of Glen Canyon Dam

Weather Station	Period Analyzed	Elevation (m)	Mean Annual Precipitation (mm)	Mean Precipitation for Monsoon Season (mm)	Mean Precipitation for Peak Month of Monsoon Season (mm)
Lower Colorado River					
Willow Beach, AZ	1967-1998	232	141	47	15
Davis Dam, AZ	1967-1998	177	148	39	13
Parker, AZ	1967-1998	128	122	44	16
K-M Plateaus					
Phantom Ranch, AZ	1967-1998	783	233	97	33
Lake Powell–Canyonlands					
Fruita, CO	1967-1998	1371	223	82	23
Dewey, UT	1967-1998	1255	236	81	32
Moab, UT	1967-1998	1225	220	86	27
Lees Ferry, AZ	1967-1995	978	153	74	26

Note: No river-level stations available for Western Grand Canyon.

CHAPTER 3

RESULTS AND DISCUSSION

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HYPOTHESIS TESTING

Null Hypothesis

H_0: *Terrace erosion rates and gully erosion rates on the terraces have remained unchanged from pre-dam time to post-dam time.*

Test 1: Determine when large gullies formed in Grand Canyon

Assessment of data, including air photos, of 23 representative catchments (see Appendixes C and D) from three geomorphic reaches between Soap Creek and Granite Park provides a synoptic view of large-arroyo development in pre-dam terraces in Grand Canyon. The pre-dam dynamic equilibrium conditions between arroyo incision and river deposition in the terraces are represented by photos taken in 1965.

Air photo analysis shows that erosion has profoundly increased since 1965 (Figure 3.1). Less than 40% of today's catchments were partially formed gullies in 1965, but by 1992 arroyos had fully formed in about 95% of catchments. The time period of the most dramatic increase is from 1973 to 1984, when new gullies were formed and most pre-existing gullies had matured into arroyos (see Appendix C). These results coincide with those of Hereford et al.(1993) who conclude that a cycle of arroyo-cutting began around 1973 and continued until 1984.

In extrapolating the rate of arroyo incision within this 32-year period to the 32-year period before the emplacement of Glen Canyon Dam, we should expect that 100% of the catchments examined would show some amount of terrace incision by1965. However, periods of arroyo cutting in the Southwest are cyclical. An extended period of arroyo cutting from about 1890 to the early 1940s (Leopold 1976) was followed by several decades of arroyo filling and floodplain formation (Hereford 1987). Despite extensive investigations, researchers have not reached a clear consensus on the causes of these changes (Cooke and Reeves 1976; Graf 1983). Any arroyos cut in Grand Canyon in pre-dam time probably coincided with turn-of-the-century arroyo cutting throughout the Southwest, but this assumption can only be deduced at this point. Nonetheless, evidence of a renewed period of arroyo cutting in Grand Canyon in post-dam time suggests that the amount of gullying has increased since pre-dam time and therefore fails to support the null hypothesis.

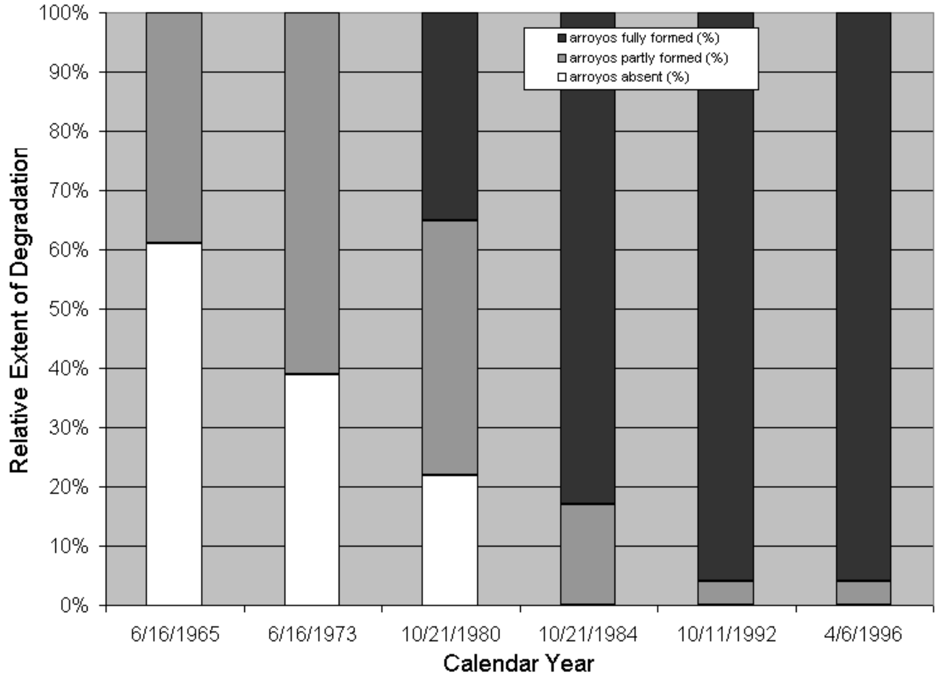

Figure 3.1. Degree of arroyo development since 1965 based on air photo analysis at 23 catchments.

As discussed in Chapter 2, historical photos could help define the time of arroyo cutting in Grand Canyon. There are numerous historical photos of the river corridor that could collectively provide a time frame during which gullies have developed in the canyon. However, such photos are extremely difficult to find, as proven by our extensive search in different archives; we found none except those uncovered by previous researchers, which are used here for this test.

Test 2: Compare amount of gully erosion on terraces in Cataract Canyon to those in Grand Canyon

Understanding the relationship between correlatable terraces and the alluvial history of Cataract Canyon provides a basis for comparison of gully incision on terraces in Cataract Canyon and in Grand Canyon. The geomorphology in Cataract Canyon is very similar to that in Grand Canyon, as discussed in Chapter 2. In our analysis of pre-dam annual hydrographs and sediment supply for the two regions, differences in amplitude are evident, yet patterns in the data roughly parallel each other.

The annual water yield through Cataract Canyon was, on average, 84% of the total water yield at Lees Ferry for the period 1929-1986. Data for Cataract Canyon are approximated by summing the water yields of the Colorado River at Cisco, Utah, and the Green River at Green River, Utah. The difference in water yield between Cataract Canyon and Grand Canyon is due primarily to input from the San Juan River (USGS 1999), which joins the Colorado River below Cataract Canyon.

Annual flood flows in Cataract Canyon show a pattern similar to those at Lees Ferry (Table 3.1.). Of the highest flood peaks during the 1900s, those in Cataract Canyon average about 80% of those at the Lees Ferry gauge (USGS 1999). The hydrograph for the last large annual flood before the dam, in 1957, shows the same general pattern for Cataract Canyon and Lees Ferry. Additional spikes in the hydrograph for Lees Ferry are a result of San Juan River monsoon flows (USGS 1999).

Table 3.1. Historical Peak Flow Events in Cataract Canyon

Green River (cfs)	**Colorado River Cisco/Fruita (cfs)**	**Date**	**Cataract Canyon[1] (cfs)**	**Lees Ferry (cfs)**	
95,000[2]	125,000	July 4, 1884	220,000	300,000[2]	(7/7/84)
62,200	72,000[3]	June 10, 1909	134,000		
68,100	76,800	June 27, 1917	130,000		
65,500	89,100	June 15, 1921	154,000	220,000	(6/18/21)
44,700	65,000	June 3, 1928	109,700	127,000	(7/01/27)
42,900	64,200	June 10, 1957	101,000	126,000	(6/12/57)
44,800	61,900	June 27, 1983	106,000	97,300	(6/29/83)
48,300	70,300	May 27, 1984	115,000	58,200	(8/12/84)
29,800	51,900	June 18, 1995	82,000	45,000	(4/1/96)

[1]Flow estimated by adding Green River and Colorado River flows; peaks are offset for each river gage and do not necessarily add up to Cataract peak flow.
[2]No gage recording; approximated from hydrologists' data (Dickenson 1944).
[3]Compiled from Fruita gage plus estimate of Dolores River flow.

Historical records of annual suspended sediment supply vary considerably between the two reaches. For the period 1930-1980 the San Juan River contributed 48% of suspended sediment to Lees Ferry, compared to 52% from Cataract Canyon (USGS Water Resources Division data, W. L. Graf, personal communication 1993). These analyses indicate that some terrace heights and widths in Cataract Canyon may not necessarily match those in Grand Canyon, depending upon the timing of San Juan River peak discharges.

We identified 13 sites in Cataract Canyon with clearly recognizable terrace sequences and geomorphic settings similar to those in Grand Canyon. Table 3.2 provides a list of sites where we have conducted field investigations, along with the type of data collected at each site. The focus of our work was in the "survey reach" from Spanish Bottom (RM 213) to Range Canyon (RM 205) (Belknap, Belknap, and Evans 1991).

Table 3.2. Study Sites in Cataract Canyon with Data Indicating River Terrace Sequence

Site Location	Geomorphic Setting	Terrace Level	Terrace Height (m)	Vegetation Community	Driftwood Present	Tree Core Sample[1]	Tree Ring Count[2] (yrs)	Artifacts Found [3]	Grain Size[4] (% si+c)
215 Mile	Talus Slope	T3		young tamarisk		GW	44		
(RM-215.0L)		T2							
		T1		desert scrub					
214 Mile	Talus Slope	T5	2.5						
(RM-213.7R)		T3		mature tamarisk					
		T2	7.8	hackberry		Hy (2)	86, 60		
		T1		desert scrub					
213 Mile	Talus Slope	T5							
(RM-213.4R)		T3		mature tamarisk					
		T2		hackberry					
		T1		desert scrub					
Red Lake Canyon	Talus Slope	T5	1.6						
(RM-212.7L)		T4	2.5	young tamarisk					
		T3	3.7	mature tamarisk		Tk	36		
		T2	5.5	mature tamarisk		GW	72		
		T1	6.7	desert scrub					56
Brown Betty Camp	Talus Slope	T5	2.0						
(RM-212.1R)		T4	3.3	young tamarisk					
		T3	4.0	mature tamarisk					
		T2	6.2	hackberry					
Rapid 4	Alluvial Fan	T5	2.5		1999				10
(RM-211.3L)	**(survey site)**	T4	3.7	young tamarisk	1995				20

Table 3.2. Study Sites in Cataract Canyon with Data Indicating River Terrace Sequence, continued

Site Location	Geomorphic Setting	Terrace Level	Terrace Height (m)	Vegetation Community	Driftwood Present	Tree Core Sample[1]	Tree Ring Count[2] (yrs)	Artifacts Found [3]	Grain Size[4] (% si+c)
Rapid 4, cont.		T3	5.1	mature tamarisk	1984	Tk	36	diagnostic aluminum cans, bottles	48
		T2	6.1	Hackberry	1921	Hy	38		44
		T1	10.3	dunes/desert scrub				preceramic flaked stone debitage, tools	24
Cross Canyon	Alluvial Fan	T5			1999				36
(RM-208.1L)	(**survey site**)	T4	1.7		1995				36
		T3	3.0	mature tamarisk	1984			diagnostic aluminum cans, bottles	36
		T2		cottonwood/ hackberry	1921	Cd(2); Hy	77, 85; 159	historic hearth (?)	46
		T1	4.2	desert scrub	1884?			prehistoric flaked stone	52
Rapid 12	Tributary Plain	T5	3.1		1999				34
(RM-206.7L)	(**survey site**)	T4	4.5	young tamarisk	1995				30
		T3	7.4	mature tamarisk	1984, 1952?	Tk	43	diagnostic cans and bottles	24
		T2	9.4	cottonwood/ hackberry	1917?, 1921	Cd, Hy	76, 65	SCA5 bottles, wire nails, saw-cut railroad ties	
		T1	11.6	desert scrub	1884?				46
Range Canyon	Debris Lobe	T5	0.9		1999				
(RM-204.8R)		T4	1.9	young tamarisk	1995				
		T3	3.5	mature tamarisk	1984			diagnostic aluminum cans, bottles	
		T2	4.5	hackberry					
Big Drop 1	Talus Slope	T5			1999				
(RM-202.8L)		T4		scour line	1995				

Table 3.2. Study Sites in Cataract Canyon with Data Indicating River Terrace Sequence, continued

Site Location	Geomorphic Setting	Terrace Level	Terrace Height (m)	Vegetation Community	Driftwood Present	Tree Core Sample[1]	Tree Ring Count[2] (yrs)	Artifacts Found [3]	Grain Size[4] (% si+c)
		T3		mature tamarisk	1984				
		T2		Hackberry	1921?				
Teapot Canyon	Debris Lobe	T5	2.3		1999				
(RM-202.7R)		T4	4.2	young tamarisk	1984			diagnostic cans and bottles	
		T2	5.8	scour line	1921, 1957?	Hy	35	wire nails	
		T1	8.9	desert scrub	1884			square nails in plank	
Ten Cent	Tributary Plain	T5			1999				
(RM-201.1R)		T4		young tamarisk	1995				
		T3	4.4	mature tamarisk	1984			diagnostic aluminum cans, bottles	
		T2	6.0	hackberry/Apache plume					
		T1	8.8	desert scrub	1884				
Imperial Canyon	Tributary Plain	T5	1.6		lake				
(RM-200.3R)		T4	3.0		lake				
		T3	5.1	scour line	1984			1984 fire extinguisher	
		T2	7.5	scour line	1921			diagnostic cans and bottles	
		T1	9.1	desert scrub	1884			square nails in beam	

[1]GW = Goodding willow, BE = box elder, Hy = hackberry, Tk = tamarisk, Cd = cottonwood

[2]Cross-checked by Arizona State University Dendrochronology Laboratory.

[3]Artifacts identified and recorded by Kate Thompson; identifications confirmed and expanded by Lynn Neal, SWCA Archaeologist.

[4]Grain size reported as percent silt and clay as determined by hydrometer method.

[5]SCA=sun-colored amethyst

For each site, we evaluated catchment processes, river dynamics, terrace sequences, and geomorphic setting. After completing a description of the terraces at 13 sites, we correlated terrace sequences using standard field techniques (see Chapter 2). Data on terraces include vegetation community, terrace height, dendrochronology, identification of modern and historical artifacts in driftwood piles, and identification of prehistoric artifacts (Table 3.2).

Five distinct terraces can be correlated throughout Cataract Canyon, several of which directly relate to the same flood events in Grand Canyon. Figure 3.2 shows a schematic illustration of the complete terrace sequence. This reconstruction is based solely on data we have collected to date, depicted in Table 3.2 and cross-referenced with the streamflow data in Table 3.1.

Stratigraphic levels are identified by age, from oldest to youngest. The youngest terrace, T5, forms the modern floodplain, which was built by flows up to 50,000 cubic feet per second (cfs) (Figure 3.2). This level provides low-water campsites for raft trips, is generally devoid of vegetation, contains fresh, small driftwood piles, and is a well-sorted medium sand (10-36% silt and clay) (Table 3.2).

The T4 level was formed by flows up to about 75,000 cfs. It was overtopped by the flows of 1995 and 1997 (Table 3.1.), which either buried immature tamarisks or ripped them away. The result is a vegetation community that consists of immature tamarisk or tamarisk seedlings and sparse annual grasses. Driftwood piles are somewhat larger than those on T5 and contain a high proportion of modern-day trash. Sediment is typically a well-sorted sand with about 20-36% silt and clay. The T4 and T5 terraces in Cataract Canyon cannot be correlated directly to the same flood events in Grand Canyon because of the presence of Glen Canyon Dam and its regulated flow.

The T3 level was formed in the late 1950s by floods exceeding 100,000 cfs (R. H. Webb, personal communication 1998) and was overtopped by the floods of 1983 and 1984 (Table 3.1). Mature tamarisk up to 45 years in age commonly grow on this level and are often buried by the 1984 flood sand. Large driftwood piles are silver in color and contain the first all-aluminum beverage cans (1957-1959) (Goodman 1998) and other diagnostic trash from the 1950s through the 1980s. This flood sand characteristically has 24-48% silt and clay. The T3 terrace is correlated with the pda terrace in Grand Canyon, on which the 1957 flood driftwood line is a distinctive and ubiquitous marker. The T3 is the key marker terrace by which critical channelization processes can be directly compared to those in Grand Canyon.

The T2 level was probably formed by floods near the beginning of the twentieth century, including a maximum flood of 155,000 cfs in 1921 (Table 3.1). This distinct terrace is often associated with a mature hackberry or Apache plume community interspersed with rabbitbrush. The oldest hackberry trees are 80-100 years in age, based on a previous study of hackberry dendrochronology (Salzer et al. 1996). Our tree-ring results show the oldest hackberry to be 159 years in age, but this tree is likely associated with a slightly higher level. We found evidence of 1921 driftwood piles inset against the riser of the T1 terrace. The 1921 driftwood piles are commonly checked and deeply weathered, with diagnostic artifacts such as wire and square-cut nails,

Figure 3.2. Schematic cross section of river terrace sequence, Cataract Canyon.

heavily weathered rough-hewn milled lumber, and UV-affected sun-colored amethyst glass. The grain size is silty fine sand (36-46% silt and clay), and several flood-sand packages make up the terrace. In the large side canyon at Rapid 12, a T2 cutbank exposure reveals three discrete river flood deposits interbedded with side-canyon stream flow deposits. In addition, we observed cut-and-fill structures within T2, suggesting that a balance between gully cutting and subsequent infilling of those gullies by the river is a process that has occurred historically in Cataract Canyon.

The T2 terrace correlates with the lmt terrace of Grand Canyon in that both are said to have been overtopped by the 1921 annual flood (Hereford, Burke and Thompson 1998), which was 220,000 cfs at the Lees Ferry gage and estimated to be 154,000 cfs in Cataract Canyon (USGS 1999). This information is roughly confirmed by our average tree-ring dates for the T2. We assume that the older trees represented the initial germination conditions following a large flood and that T2 has not been flooded since that time (R. H. Webb, personal communication 1998). Driftwood and associated artifacts of the early 1900s are distributed across the entire T2 surface.

The highest terrace level, T1, is a prehistoric terrace that was built by floods exceeding about 225,000 cfs. These sands are commonly mounded into eolian dunes in which prehistoric artifacts such as lithic flakes and tools can occasionally be found. On August 2, 1999, during the final mapping trip through Cataract Canyon, SWCA archaeologist Lynn Neal accompanied the geomorphology team to document cultural resources at two study areas. The first site is on the left bank of the river above Rapid 4, creatively named the Rapid 4 site. The site's artifacts are on T1 and are exposed primarily in deflated areas surrounded by low eolian dunes and debris-flow mounds to the south. The site is in a low, west-northwesterly sloping swale bounded on the west by a gully, on the east by a side canyon to the river, on the north by the riser of T1, and on the south by the debris-flow mounds. Artifacts were flagged and described, and the site was then mapped using a tape and compass. Flaked stone tools were point located on the map and were also drawn (Figure 3.3). The size and quality of manufacture of these dart preforms and the associated debitage suggest a preceramic or pre-Puebloan period (pre–A.D. 300-500) use or occupation.

Figure 3.3. Diagnostic flaked stone tools from the Rapid 4 site: white silicified chert (PL1), white chalcedony (PL2), red jasper (PL3), red jasper (PL4), and red jasper/limestone (PL5). Tools are shown actual size, in plan and cross section of each broken edge.

The Rapid 4 site contains well over 1000 flaked stone artifacts densely concentrated in a roughly 14 × 11-m area at the site's center, surrounded by a moderately dense flaked stone concentration. The entire site area measures 78 m east-west by 29 m north-south. The majority of artifacts are medium and small tertiary flakes generated from interior core reduction and initial biface reduction; late-stage biface thinning pressure flakes are present as well. There are some large tertiary flakes, a few secondary flakes, and no primary flakes. The cherts, jaspers, and chalcedonies that are present are all of high quality and appear to be heat treated. Great care was taken in securing premium raw materials to reduce (by percussion), heat, and then pressure flake, making large, thin knives and, presumably, dart points. Colors and types most represented are red jasper; white, mottled red and orange, brown, and gray (light and dark) cherts; white and pinkish red translucent chalcedonies; and yellow jasper. Some of the chert is silicified, and some (browns and oranges) has limestone attached; all of the material appears to have been acquired locally or within a relatively short distance. In summary, this site is a preceramic period limited-activity flaked stone scatter. The site's artifacts indicate late-stage interior core reduction, meaning that the raw materials were being reduced before being transported to the site, where they were further reduced and shaped into tools.

The second site is also on the left side of the river, downstream from Cross Canyon and just above Rapid 10. Neal documented what appeared to be the first evidence of a site being exposed on August 4, 1999, consisting of eight light gray chert flakes (1 secondary, 4 tertiary, and 3 biface thinning) in an area less than 5 m in diameter. These flakes represent a single-episode reduction of an interior core and subsequent biface reduction. The artifacts are probably eroding from the southern slope of a T1 dune, since the flakes were visible only in the vicinity of rodent holes.

These sites are not unlike those documented at roughly the same terrace level the Grand Canyon. Preceramic sites in the Grand Canyon often date to the Late Archaic, as evidenced by projectile point types (Fairley et al. 1994). These aceramic and Archaic sites are often found deeply buried in alluvium of Puebloan age (ap), a possible T1 equivalent, or on or near the surface of the striped alluvium (sa), which represents the highest T1 surface in Cataract Canyon.

The front edge of the T1 terrace was probably overtopped by the flood of 1884 (Table 3.1). Extremely deteriorated driftwood lines set into the soil were observed in this position at several of the sites. At Calf Canyon and Imperial Canyon enormous, extremely decayed driftwood piles, containing less than 5% milled lumber with square-cut nails still in the beams, lie above both the 1984 and the 1921 piles (Table 3.2). The height of the piles, the deteriorated condition of the wood, and the artifacts found seemingly correlate with the 1884 driftwood in Grand Canyon as described by Hereford and others (1993). One barely discernible driftwood line was identified beyond the 1884 line, but we found no associated artifacts or datable materials to indicate whether this material is older than the flood of 1884 . The vegetation on this level consists of mature desert scrub plants such as four-wing saltbush, Mormon tea, and prickly pear cactus, all of which are growing out of very thick (3-5 cm), dark cryptobiotic soil. The sedimentology is also distinct, consisting primarily of silt (46-56% silt and clay), except for dune portions that are primarily fine sand (24-34% silt and clay).

The T1 terrace of Cataract Canyon is broadly equivalent to the ap and sa terraces of Grand Canyon. Its height above the river, the xeric vegetation community, the gentle slope toward the river, the presence of preceramic lithic materials on the surface, and its great thickness indicate that the T1 is many hundreds of years in age. It is as laterally extensive in Cataract Canyon as the ap and sa terraces in Grand Canyon. Driftwood was deposited on its front edge during the late 1800s by either the 1884 flood (Table 3.1) or the more poorly known and probably much larger flood in about 1862 (O'Connor et al. 1994). Evidence for the 1862 flood has not been identified in Grand Canyon, although Hereford, Burke, and Thompson (1998) suggest that these two large floods probably did not overtop the ap or sa terraces. Despite the lack of conclusive evidence, we propose that the T1 terrace was deposited over many hundreds of years during sa and ap time and has only recently been wind-scoured into a hummocky surface, leaving buried cultural materials exposed on its modern surface.

With a correlation of terraces between Grand Canyon and Cataract Canyon demonstrated, we can now compare the two settings for relative amounts of gully erosion. In comparing three similar geomorphic areas in the two canyons, we found that gully density is higher for two of the areas in Grand Canyon by 1.5 times (Table 3.3). We also investigated gully depth in the ap/T1 levels (Table 3.4) and the number of catchments that are river based. Results show that gullies at the three areas in Grand Canyon are over four times deeper than those in similar areas of Cataract Canyon and that the number of river-based streams is two times greater in Grand Canyon than in Cataract Canyon.

Table 3.3. Gully Density of Three Paired Areas, Grand Canyon and Cataract Canyon

Sites Compared	**Length of Area (m)**	**Number of Catchments**	**Average Distance between Gullies (m)**	**Gully Density (m)**
Comparison 1				
Palisades Creek	42	3	14	0.07
Cross Canyon	42	2	21	0.05
Comparison 2				
Upper Unkar	112	8	14	0.07
Rapid #12	108	4	27	0.04
Comparison 3				
Tanner Canyon	112	4	28	0.04
Rapid #4	83	3	28	0.04

Table 3.4. Comparison of Degree of Gully Incision, Grand Canyon and Cataract Canyon

Indicators of Gully Incision	**Grand Canyon**	**Cataract Canyon**
Mean gully depth in ap/T1 terrace (m)	2.43 (n=15)	0.56 (n=9)
Range of gully depths (m)	0.50 - 4.0	0.12 - 0.85
River-based catchments (%)	53	22

In general, gully degradation of the terrace sequence in Cataract Canyon is relatively minor compared to that in Grand Canyon. Although the frequency of large monsoon season precipitation events appears to be slightly less than in Grand Canyon, we postulate that the relative rarity of gully-forming processes is largely the result of redeposition by large annual floods that continue to occur in this reach.

Falsification of the Null Hypothesis

Results of the first test show that gully erosion has increased from pre-dam time to post-dam time in Grand Canyon. Since we were limited in our analysis by the scarcity of photos from pre-dam time (1965), in contrast to the many years of photography spanning post-dam time, in the second test we used Cataract Canyon as a pre-dam analogue to sites in the Furnace Flats reach of Grand Canyon. The amount of gullying in Cataract Canyon is far less than that in Grand Canyon. Furthermore, the extent to which gullies have downcut in sandy terraces is minimal compared to that in Grand Canyon. Results of these tests indicate failure to prove the null hypothesis. We therefore pursued alternate hypotheses that could explain why gully erosion has increased from pre-dam time to post-dam time.

Climate-Variation Hypothesis

H_1: *Gully erosion on alluvial terraces associated with archaeology has increased from pre-dam time to post-dam time due to variation in precipitation patterns.*

Test 1: Evaluate previous research on decadal-scale precipitation variations that may be responsible for increased erosion rates

Hereford and Webb (1992) conducted an examination of variation in warm season rainfall across the southern Colorado Plateau for the period 1900-1985 in an attempt to relate precipitation patterns to arroyo cutting and filling episodes. The results of their standardized anomaly index show that the dam was constructed in the middle of the longest period of below-normal warm season rainfall in this century, 1942-1980. Except for a dry period from 1933 to 1940, warm-season rainfall was generally higher than normal from 1906 to 1941 and became much higher than normal again from about 1980 to the present (Hereford and Webb 1992; Hereford et al.1993;

Webb, Griffiths, and Melis 2000; Webb et al. 2000).

Hereford and Webb (1992) and Webb, Griffiths, and Melis (2000) determined that the driest warm-season period in this century was from 1973 to 1980. The relatively stable condition of arroyos from 1965 to 1973, as shown in air photo and repeat ground level photography of Hereford and others (1993) and Hubbard (2000), correlates with this dry period . From those same analyses, the wettest warm-season period in this century, from 1980 until the present, correlates with the nearly complete down-cutting of arroyos in Grand Canyon.

Standardized seasonal precipitation data for the western Grand Canyon area (Webb et al. 2000) and decadal standardized precipitation data for the larger region (Webb, Griffiths, and Melis 2000) show very large multi-year winter rainfall periods in the first decade and last two decades of the twentieth century. These three decades also experienced unusually high summer-season rainfall. Winter-season rainfall was generally at or below normal during the intervening seven decades.

The evidence from these century-long analyses of winter and summer rainfall suggests that arroyo cutting in Grand Canyon could have occurred in 1905-1933, 1940-41, and 1980-1995. The intervening periods, particularly the period from 1942 to 1980, probably did not cause the amount of gully erosion of terraces witnessed from 1980 to the present (Hereford et al. 1993; Leap et al. 2000). There appears to be a cause and effect relationship between periods of unusually high precipitation and arroyo cutting during the past two decades. However, if arroyo cutting were to consistently correlate with any period of high precipitation, then little of the alluvial terraces with cultural remains would be left in Grand Canyon. That this is not the case points to some other geomorphic threshold that has been exceeded, such as loss of sand in the river system.

Test 2: Investigate variations in monsoon season rainfall at equivalent time periods before and after closure of Glen Canyon Dam

High-intensity daily and monthly precipitation data are plotted for weather stations between Grand Junction, Colorado, and Parker, Arizona (Figure 3.4). The solid line with a perfect slope of 1 divides weather stations that recorded higher values for the pre-dam period from those recording higher values in the post-dam period. Points that lie on the solid line show no change between the pre-dam and post-dam periods.

Plot A in Figure 3.4 shows that stations recording more than 50 mm per month are evenly distributed around the line of equal events and lie fairly close to the line ($R^2 = 0.90$). Station data grouped by physiographic region show that two regions, Lower Colorado River and Western Grand Canyon, have recorded more monsoon precipitation in post-dam time, with increases in 50 mm/month events by 1% and 3%, respectively. The other two regions, the K-M Plateaus and Lake Powell–Canyonlands, have recorded fewer of these events since closure of the dam, with decreases of 3% and 2%, respectively.

Figure 3.4. Relationships of monsoon precipitation events between equal periods in pre-dam time and post-dam time: (A) percent of monthly precipitation events exceeding 50 mm, and (B) number of days exceeding 25 mm.

Plot B in Figure 3.4 shows that, for the 25 mm/day data, stations are evenly distributed but are widely scattered about the line of equal events ($R^2 = 0.30$). The large scatter is probably due to the sporadic and localized nature of these intense precipitation events. Station data grouped by physiographic region show that two regions have increased in high-intensity events from pre-dam to post-dam time: the Lower Colorado River region has increased by 46% and the K-M Plateaus have increased by 7%. Fewer of these events have been recorded in the other two regions since closure of the dam, by 3% for Western Grand Canyon and 22% for Lake Powell–Canyonlands.

Both plots show almost no difference between the best-fit line and the line of equal events. For the period of record examined, general change in monsoon activity for the greater Colorado River vicinity shows little difference between the pre-dam and post-dam time periods examined. Within the Grand Canyon region, river level station data for Lees Ferry and Phantom Ranch show a decrease in both indices of monsoon intensity from pre-dam to post-dam time. This is in contrast to high-elevation station data for Grand Canyon and Fort Valley, which show an increase in both of these parameters. Eleven of the 13 stations record the same direction of change for both precipitation indices, suggesting that both indices are valid measures of monsoon season intensity.

Although these plots do not show a regional temporal change in monsoon season precipitation, they do show an interesting spatial variation. All stations that lie east of a line along the crest of the Kaibab-Mogollon plateaus show a decrease in post-dam monsoon precipitation, whereas nearly all stations to the west of this geographic high show an increase in the same period. Further research is needed to determine the validity of and possible explanations for this trend.

This temporal analysis of monsoon precipitation for the southern Colorado Plateau region is not inconsistent with the standardized anomaly indices for monsoon precipitation developed by other workers (Hereford and Webb 1992; Webb, Griffiths, and Melis 2000), which do not show an obvious change in the fluctuation about the mean. Although both of these analyses show a very large positive anomaly beginning about 1980, it is balanced out by an equally large negative anomaly in the 1970s. Standardized anomalies for the pre-dam period fluctuate less around the mean value than do those for the post-dam period. Nonetheless, it seems likely that the high monsoon season anomalies in the 1980s and 1990s resulted in uncommonly high gully erosion rates in Grand Canyon, especially considering the reduced sediment supply and absence of large annual floods as a result of the emplacement of Glen Canyon Dam.

Base-Level Hypothesis

H_2: *Gully erosion on alluvial terraces associated with archaeology has increased from pre-dam time to post-dam time due to base-level effects.*

Test 1: Report on rebuilding of sand bars that buttress pre-dam terraces and infill gullies in Grand Canyon versus those in Cataract Canyon

Pre-dam floods maintained sand bars at a higher base level than at present. During the 41-year period prior to closing of the dam (1922 to 1962), annual peak floods of the river ranged from 105,000 cfs to 127,000 cfs (USGS 1999) and inundated the pda terrace at least 10 times (Hereford et al. 1998). Likewise, the river flooded the level of the umt deposit at least nine times from sometime between A.D. 1280 and 1470 up until 1883, as determined from the Lava Canyon profile (Hereford 1996).

The 1884 annual river flood of about 300,000 cfs (USGS 1999) overtopped the lmt terrace at most locations, with the exception of a few anomalous sites. This flood inundated the ap/sa terrace at Axehandle Cove (RM 2) in Marble Canyon (O'Connor et al. 1994) and possibly inundated the lowest ap levels at Palisades Creek (RM 65) in Furnace Flats as well. We observed flood sand deposited inside of the McCormick cabin, which was built near the turn of the century (Helen Fairley, personal communication 1999) on ap sand (Hereford 1996). There is also evidence that the flood of 1884 or one in the mid 1800s may have overtopped the ap level at Arroyo Grande in western Grand Canyon. A radiocarbon sample from a feature at the surface of the ap level dates to 170±50 B.P. These pieces of evidence are profoundly significant, in that the archaeological terraces could have been inundated with flood sand more often than has been thought in the past.

Research conducted by Burchett, Coder, and Hubbard (1996) indicated that the beach-habitat-building flow (BHBF) of 1996 had an overall positive effect on 18 near-river cultural resources studied. At three out of four locations studied by Yeatts and others (1996), new sand was deposited in the mouths of arroyos. The authors of both studies express concern for the longevity of these fresh deposits, as the volume of sand deposited was not large enough to offset the pervasive effects of erosion occurring upstream in the catchment and at river level (Yeatts et al. 1998)

Duane Hubbard of the RCMP is currently rephotographing sites shown in historical photos. A photo taken in the Palisades area in 1923 by Julius Stone (Figure 3.5A) shows the extent to which sand was deposited near the river. While Hubbard has not yet matched this photo, the setting is now gravel with two river-based streams and several terrace-based streams that drain past this level (see Hereford 1998 map). Likewise, a photo taken at 222 Mile in 1923 by E. C. La Rue (Figure 3.5B) shows a relatively high sand bar, which is equivalent to the pda level. Any streams that crossed this area were periodically infilled, temporarily raising the local base level.

The photos in the Bill Belknap collection (NAU Special Collections) offer some general insights about how pre-dam sand provided a higher base level for the mouths of channels in Grand Canyon. Figure 3.6A is a view downstream taken at the "old Unkar camp" (RM 72.2R) by Bill Belknap during a 1960 jet boat trip, prior to his landmark up-run of Grand Canyon with Buzz Belknap (Buzz Belknap, personal communication 1994). This locality was favored as a campsite by river-runners in the 1970s and early 1980s.

Figure 3.6B is the repeat photo taken in October 1998. Note that most of the white sand is missing from the area downhill of the orthogonal boulder, leaving a strip of white sand behind and to the right of the boulder (here mapped as 1983 flood sand). The upper slopes were severely

Figure 3.5. Historical photos showing elevation of sand bars below archaeological sites: (A) Julius Stone photo of Palisades Creek area taken in 1909, and (B) E. C. LaRue photo of 222 Mile taken in 1923.

Figure 3.6. Repeat photos showing change at "old Unkar camp": (A) Belknap photo of 1960, and (B) repeat photo of October 1998.

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impacted by the summer monsoon of 1983, and the high flows of 1984-1986 caused the scarp retreat seen today (Regan Dale, Kenton Grua, Andre Potochnik, personal communication 1999). The removal of sand from beneath the large orthogonal boulder caused it to tilt downward toward the river. Note also the high degree of tamarisk encroachment in Figure 3.5B. Furthermore, the reddish sandy slope in the background was once covered with fresh eolian sand that was blown upslope (Figure 3.6A). Today this slope is deeply incised, and archaeologic features are exposed in gullies. We interpret the combination of rainfall-induced gullying and scarp retreat as accelerating erosion of the upper terraces. We speculate that the cut-off of fresh sand supply from the river has interrupted any renewal of wind-blown sand to upper slopes and terraces. This cut-off is due in part to the encroachment of tamarisk near the river, blocking entrainment of sand particles to upper terraces.

Figure 3.7A was taken by Belknap during his 1963 sportyak trip through the Grand Canyon on flows of 1000 cfs following closure of Glen Canyon Dam. The location is a view downstream of the large willow tree at Granite Park (RM 208.9L). Note the high embankment of sand on the river side of the tree.

Figure 3.7B is a repeat photo taken in April 1996 just after the BHBF and during the low flow of 8000 cfs. While the BHBF rebuilt the height of the sand bar, the amount of sediment deposited was insignificant compared to what pre-dam floods were capable of depositing. The constant renewal of fresh sand in pre-dam time maintained the level of terraces near the river, suggesting that restorative processes of river deposition and eolian redistribution of sand were considerably more active than today.

Repeat photography of several sand bars in Cataract Canyon provides evidence of annual flood renewal to lower terraces. Figures 3.8, 3.9, 3.10, and 3.11 show the level of infilling after the spring runoff of 1999. Figure 3.8 illustrates the recirculation zone at Cross Canyon, where a cutbank recorded in March 1999 was buttressed with a large amount of sand in August 1999. The associated gullies (all of which are terrace based) at this site remained stable during the two-year period of study. Figure 3.9 shows the effects of infilling of a river-based gully at the channel margin bar of Rapid 12. It appears that the face of the sand bar was partly eroded and redistributed higher up, infilling and covering the pre-existing gully. It also appears that the bar has built upward, creating a new, higher level that the channel must now cross. Terrace-based streams in this area remained stable over the two-year study.

Figures 3.10A and B show the cycle of redeposition from the annual flood of two years at Teapot Canyon. Photo 3.10C then shows subsequent gully erosion caused by a severe monsoon season. Presumably these will be infilled and this level will be built upward again with the next annual flood. Figures 3.11A and B show the cycle of monsoon-season gullying across the sand bar at Brown Betty Camp and subsequent sand coverage. This series depicts severe gully erosion in August 1997, with eolian infilling from floods of 1998 and 1999.

Repeat topographic surveys of Rapid 4, Cross Canyon, and Rapid 12 depict the volume change at each site that occurred after the 1999 spring flood. Survey results allow for quantification of annual flood impacts on the terrace sequences and small catchments in Cataract Canyon that otherwise cannot be determined from oblique photos.

To be able to make a confident comparison of pre– and post–annual flood conditions, we conducted surveys under similar river flow conditions. The average estimated discharge through Cataract Canyon for the pre-flood survey on March 20-22, 1999, was 9900 cfs; in comparison, the post-flood survey on August 2-4, 1999, was 12,900 cfs. The stage height difference between pre- and post-flood survey was less than 0.5 m. This small variation in stage enabled reasonably accurate comparison of the two topographic surveys. The hydrograph for the peak runoff season (April-July) in 1999 was very similar to the long-term median for this period. The peak discharge in 1999 of 47,000 cfs represents average annual runoff, as the long-term median peak discharge through Cataract Canyon is 43,000 cfs.

Figures 3.12 through 3.20 show the results of the surveyed areas, depicting mapped areas with volume change and cross-sectional views of change. Table 3.5 summarizes results of the two survey periods with a standardized index of net change to facilitate comparative results between areas.

Table 3.5. Volume of Sand Lost or Gained at Three Topographically Surveyed Terrace Catchment Study Areas in Cataract Canyon

Study Site	**Sand Volume Cut (m3)**	**Sand Volume Fill (m3)**	**Net Sand Volume Change (m3)**	**Ratio of Net Change by Volume/Area (m)**
Rapid 4	-187.6	+145.5	-42.1	-0.02
Cross Canyon	-400.9	+2677.6	+2276.7	+0.75
Rapid 12	-811.2	+1.9	-809.3	-0.42

The Rapid 4 catchment area lies adjacent to a large pool above the rapid and is a channel margin bar with no recirculation zone at moderate flows (Figures 3.12 and 3.13) (see Appendix E for location of site). This site shows a minor amount of change (0.02 m/m2), which could be attributed to error in the repeat topographic survey, but we will assume the change is real. Generally the site remained unchanged except for about a 1-m cut from the sand embankment (Figure 3.14) from a small area on the downstream end of the surveyed area. Just beyond the upstream end of the survey area, we observed a new sand deposit 1-2 m deep about 25 m into the mouth of the adjacent tributary drainage. This deposit serves as a temporary rise in base level for the tributary drainage. Otherwise the annual flood did little to impact this site, and study catchments remained stable.

The Cross Canyon study area is a large recirculation zone (Figures 3.15 and 3.16) (see Appendix E for location of site) that had a 2.5 m vertical cut bank prior to the annual flood. The eddy gained a very large amount of sand as a result of the annual flood (Table 3.5). The four profiles show a dramatic change in the configuration of the bar complex (Figure 3.17). The annual flood filled the entire eddy with a separation bar of sand more than 2 m deep and 2,677 m^3 in volume, eliminating

Figure 3.7. Repeat photos showing change at Granite Park recirculation zone: (A) Belknap photo of 1963, and (B) repeat photo of October 1998.

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Figure 3.8. Repeat photos showing effects of annual flood at Cross Canyon recirculation zone: (A) March 1999, and (B) August 1999.

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Figure 3.9. Repeat photos showing effects of annual flood on Rapid 12 channel margin bar: (A) March 1999, and (B) August 1999.

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Figure 3.10. Repeat photos (view upstream) of Teapot Canyon area showing cycle of periodic deposition from annual flood and subsequent gully erosion from monsoon season: (A) September 1998, (B) March 1999, and © August 1999.

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Figure 3.11. Repeat photos showing gully infilling at Brown Betty Camp, Cataract Canyon: (A) August 1997, (B) August 1998, and © August 1999.

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Figure 3.12. Cataract Canyon Rapid 4

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Figure 3.13. Cataract Canyon Rapid 4

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Figure 3.14. Cataract Canyon Rapid 4

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Figure 3.15. Cross Canyon

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Figure 3.16. Cross Canyon

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Figure 3.17. Cross Canyon

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Figure 3.18. Cataract Canyon Rapid 12

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Figure 3.19. Cataract Canyon Rapid 12

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Figure 3.20. Cataract Canyon Rapid 12

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the recirculation zone at low flows. The separation bar is flat-topped with a return current channel 1-2 m deep scoured along its back side near the shore. Two large backwater ponds formed in the return current channel as the river stage dropped during July. A part of the pre-flood cut bank retreated farther during the annual flood, resulting in only a minor amount of sand erosion (400 m^3) compared to the large gain in the eddy. Catchments A and B remained stable, and the level to which they will try to drain is now the newly formed separation bar. This recirculation zone is somewhat similar to the one that Yeatts (1996, 1998) studied at Palisades Creek. He recorded a ratio of net change at Palisades of +0.04 m/m^2 after the 1996 BHBF of 45,000 cfs, a substantial difference from the net change at Cross Canyon of +0.75 m/m^2. We surmise that the difference is the amount of sediment available for deposition in Cataract Canyon.

The Rapid 12 catchment area is a channel margin bar (Figures 3.18 and 3.19) (see Appendix E for site location) below the rapid that lies across from a large mid-channel gravel bar. This site has no recirculation zone at lower stages, and it could form a reattachment bar at flows above 100,000 cfs, which approximates the flow in 1984. This area lost 809 m^3 from its embankment after the 1999 annual flood and did not gain as much new sand as appeared to be the case in the repeat photos. The entire bar was cut back by 1-2 m (Figure 3.20). A deep gully in catchment D that had incised through the entire terrace sequence during the 1998 monsoon season was infilled by the flood, causing it to become terrace based on T4 rather than river based as it had been before the annual flood. The mouth of the stream gained only 0.6 m^3, suggesting that the terrace was beveled off and the depth of gully cutting was therefore less apparent.

The results of this survey indicate that sand deposition does not necessarily occur at these sites every year. Since sand deposition is dependent on stage level and flow duration as well as sand supply, we predict that if the flood hydrograph had been of shorter duration and higher peak, less scarp retreat would have occurred at the Rapid 12 area and that, in consequence, less of the available sand supply would have been transported downstream into Lake Powell. Unfortunately, we can only confidently compare results from Cross Canyon of Cataract Canyon to Palisades Creek in the Furnace Flats reach of Grand Canyon. Although the value of percent gain (volume per unit area) is higher for the Cataract Canyon site than for the Grand Canyon site, we need a larger sample set to confidently cross-compare sites. The survey results do confirm that dynamic equilibrium of sand bar restoration varies from site to site and from year to year. Moreover, persistent recirculation zones such as the one at Cross Canyon consistently show deposition with the annual flood (John Weisheit, Cataract Canyon guide, personal communication 1999).

A further piece of evidence on the process of gully infilling is the presence of cut-and-fill structures, specifically, alluvial sands that were once dissected by small streams and since then have been infilled by river sand or eolian sand. These structures are observed in the walls of large gullies or tributary cuts at several sites in Grand Canyon, including Arroyo Grande, Lower Tanner, Lava Canyon, and Palisades, for the most part in the umt and ap units. The same type of cut-fill structures were observed at the tributary cut of Rapid 12 in the T3 level. This suggests quasi-equilibrium conditions between catchment erosion and periodic sand deposition. The lack of infilling of these large gullies in post-dam time confirms that the interruption of large annual sediment-laden floods by the dam has shifted the balance. Catchment erosion processes are now dominant, accelerating erosion of cultural materials contained in those terraces. Only small sand plugs in river-based gullies have been measured to date, but they cannot endure runoff events from the catchment (Yeatts 1998).

A final piece of anecdotal evidence of gully infilling comes from investigations of the Paria River floods of 1997-1999 (Richard Hereford, personal communication 1999). The Paria River overtopped its bank and filled in many small catchments with sand that is 2-3 m deep. Today the catchments have formed alluvial fans and are backing up with sediment due to their own base-level change.

Test 2 - Assess catchment and river processes at each study site in Grand Canyon

Specific catchment and river processes were identified (see Table 2.2), and each was given a score as to whether it was operable at a specific site. The total score from each site indicates whether it supports or fails to support the base-level hypothesis. Characteristics of individual sites are listed in Appendix B. Figure 3.21 shows the degree to which all sites support this hypothesis (data provided in Appendix C).

Figure 3.21. Percent of surveyed sites (n = 119) that support or negate the current base-level hypothesis. Each catchment evaluated using data in Table 2.2.

Only eight sites (7%) do not support the hypothesis (score=2), and 18 sites (15%) weakly support the hypothesis (score=3). These sites exhibit pre-dam arroyo-cutting processes or are non-depositional areas, processes that are unrelated to the presence and/or operations of the dam. Most base-level characteristics (listed in Table 2.2) are present at the remaining 93 sites (78%), supporting the hypothesis (score > 3). Specifically, they are long-lived recirculation zones with no pre-dam arroyo cutting and little evidence of pre-dam bank retreat. Scores for all sites are listed in Appendix B.

In the post-dam era, streams must cross lower terrace levels that once were bars with higher elevations. In considering possible sand renewal to sand bars in the post-dam setting, we assessed the presence of post-dam flood sands at each site compared to the presence of pda sand (Figure 3.22). The 1996 and 1983 flood sands have generally benefited beach building in Grand Canyon (Hereford et al. 1996; Kaplinski et al. 1999; Yeatts 1998). Figure 3.22 shows the number of sites containing these deposits and the number with to the pre-dam annual flood deposits (pda). Over half of all study catchments have either 1983 or 1996 deposits, yet only 44 catchments have both deposits. In comparison, 80 catchments show evidence of pda deposits or remnants. Thus, the number of sites with 1983 sand deposits closely approximates the number with pda deposits. These results show the effectiveness of the 1983 event, which built nearly as many sand bars as were built by pre-dam floods (pda unit).

Figure 3.22. Number of sites containing 1996, 1983, or pda flood deposits.

Finally, wind is a major mechanism in restoring sand to gullies in Grand Canyon and probably maintains the level of higher terraces by blowing sand upslope. Figure 3.23 shows the results of active eolian sand that has directly infilled parts of study catchments. Half of the catchments have some kind of eolian deposition, and 42% have active eolian deposition within the catchment area.

Figure 3.23. Percent of catchments that exhibit varying degrees of eolian activity. Units found within catchments are: none = no eolian activity, eo = old eolian dune, and % ea = percent of catchment with active eolian sand.

These results do not account for wind-deflated areas, nor do they include eolian deposits that lie below or near the mouths of catchments. Results do suggest that wind is extremely influential in resupplying sediment to higher terraces. However, periodic sediment renewal by the river is imperative for this process to operate. A prime example is at the Palisades Creek type area (Plate 3), where deflation of dunes probably has promoted increased rates of gully incision because the sediment supply by the river has been severely reduced. In 1973 this was a partial gully that was blocked by the pda level and related dunes. By 1980 this channel had pushed through the dunes and became river based. Another example of this is seen at the Lower Tanner area, where stream C (type stream in Plate 6) has breached the sand dunes and is now river based..

Based on evidence presented in these two tests, we conclude that the base-level hypothesis cannot be rejected. We needed to use as many lines of investigation as possible because the concept of base-level change with regard to dams and their operations is poorly understood, although it is a widely known and generally accepted concept with regard to stream development. Several lines of investigation—using available historical photos and repeat photos, making comparative assessments of sand bar renewal in Grand Canyon versus and in Cataract Canyon, and examining processes operating at individual sites in Grand Canyon—aided us in understanding base-level processes. Therefore, we feel that this hypothesis needs to be refined to include the importance of sediment-laden flood flows and subsequent eolian action. We therefore propose a refined hypothesis to be called the "restorative base-level hypothesis."

THE GEOMORPHIC MODEL

Results of hypothesis testing show that increases in precipitation in the 1980s correlate with a large amount of gullying in Grand Canyon. These periods are not unusual, as above-normal precipitation has occurred in several periods throughout pre-dam time. However, the amount of arroyo cutting and gullying was not evident in 1965 aerial photos or from the few historical photos uncovered by researchers, indicating that some geomorphic threshold besides climate has been exceeded. This threshold component points to lack of sediment renewal to the terraces. The potential for advanced gully erosion has increased because of decreased periodic deposition of fine sediment on terraces. In this next section, we explore the kinds of geomorphic settings that control the depositional environment.

Geomorphic Settings

The geomorphic setting exerts a profound influence on the type of sand terrace in each area and how that area is affected by runoff events. Small streams that drain across a particular geomorphic setting exhibit a high degree of similarity. Classifying streams into a geomorphic setting allows for general characterization of a wide variety of small catchments along the river. Some catchments divide or include two adjacent settings, in which case they are categorized according to the dominant setting (see Figure 2.3). The type-area maps display many of the details of each setting, which are discussed in sections that follow. Hydraulic conductivity values are taken from Table 2.7.

Alluvial Fan Setting

In wide sections of the canyon dominated by shale lithologies, alluvial fans are commonly deposited by flashy runoff from small tributary canyons. A variation of this setting occurs where a talus slope merges downslope with coalesced alluvial fans. These alluvial fans of shale commonly coalesce into small alluvial fan complexes (see Figure 2.3), typified in the reach between Nankoweap Creek and Unkar Creek. Gravel is transported by local flash floods toward the river, where it is typically interbedded with high river sand deposits. Interbedding of shale with light brown river sand is the feature for which the striped alluvium (sa) (Figure 1.2) was named (Hereford 1996).

The type setting at Lower Nankoweap with paired catchments, N and Q, best illustrates the alluvial fan setting (Plate 2). Catchment N is terrace based on the lmt terrace and has a discontinuous channel across the ap terrace. Catchment Q is river based. Both catchment areas are very large and similar in size. They drain from the east flank of Nankoweap Mesa down a very steep series of cliffs and slopes of Cambrian strata onto a deeply dissected talus slope, where they are reworked into short, broad alluvial fans of gravel. The alluvial fans are interbedded with the ap and sa terraces, which are also very broad and well-vegetated. A robust xeric vegetation community is a result of the eastern exposure and minimal evaporation. Because of the nature of this setting, many channels cross the alluvial fan but then discontinue. Typically a thalweg will occupy a shallow swale for 15-30 m and terminate in a small alluvial fan. Farther downslope another short thalweg segment will then appear. Large nickpoints have formed in the ap terrace riser below, but no thalweg can be directly traced to it.

The discontinuous nature of gully development on the ap terrace despite large drainage areas is likely due to alluvial fans creating distributary networks. Runoff in this area easily infiltrates (K = 0.007 cm/s) into the broad upper ap terrace through two mechanisms: interbedded gravel layers from alluvial fans of Bright Angel Shale and the extensive roots of perennial acacia trees. Numerous holes and large roots in the ap terrace riser have locally caused piping and subsequent surface collapse and have initiated nickpoint migration.

Tributary Plain Setting

Large tributary canyons with abundant fine-grained source material in their headwaters tend to form extensive, low-gradient fans at their mouths (Figure 2.3). Most of these deposits are of debris-flow origin and are interbedded with hyper-concentrated flood flow and turbulent flow deposits (Hereford, Burke, and Thompson1998). Typically, the side-canyon stream has incised a channel into the fan complex, leaving a broad, perched plain rarely overtopped by the primary stream channel. These low-relief gravel plains have been partly overtopped by large river flood events, resulting in extensive terrace deposits (Hereford et al. 1996) that were periodically used by prehistoric cultures living in Grand Canyon (Fairley et al. 1994; Schwartz, Kepp, and Chapman 1981). Local catchments in these settings can originate from the talus-bedrock slopes adjacent to the canyon mouth or on any part of the broad fan surface. As a result, catchment area sizes vary, ranging from extremely local "postage stamp" basins to broadly extensive ones. Eolian deposition is common in large areas of the tributary plain, as at Palisades Creek.

The catchments H and H' at Palisades are designated as type catchments for the tributary plain (or deltaic fan) setting (Plate 3). Their catchment areas are very large, extending to the top of a high ridge of Tapeats Sandstone, Dox Formation, and Cardenas Lava. Catchment H is river based, while H' is terrace based on the pda terrace. Both catchments drain from a playa lake–coppice dune complex deposited on the ap terrace at the base of the talus slope (Hereford 1996). Catchment H' is a shallow, incipient gully that has low vulnerability for ponding and overflow because the playa is now being continuously drained by the deep gully system of Catchment H.

The coppice dunes had apparently once acted to impound surface water in the playa due to the accumulation of clay and evaporites weathered from the overlying rock formations. Infiltration tests on the playa show negligible hydraulic conductivity values ($.0007 \times 10^{-3}$ cm/sec). Numerous tree roots project outward from the scoured flanks of coppice dunes closer to the river, suggesting wind deflation. We interpret this to mean that wind deflation of the dune complex reduced its ability to continually block water in the playa, resulting in overflow and gully cutting of Catchment H. However, with a fresh supply of a large amount of flood sand, this area could be infilled again. Evidence of this process was recorded by Yeatts (1998). One year after the 1996 BHBF, survey results showed a gain in volume of sand in the area just above the high flow, which Yeatts attributed to the eolian effects of sand redistribution to higher terrace levels.

Talus Slope Setting

Reaches of the river corridor that lie between extensive regions of tributary deltaic fans are commonly dominated by talus slopes. In these reaches, lobate talus cones create an irregular gravel embankment against which channel margin sand bars are deposited (Figure 2.3). The bedrock headwater areas of these catchments are close to the river and have a very high runoff efficiency because talus cones reach an angle of repose at 33^{o}. The typically steep slope funnels water onto the upper sand terrace. However, the lithology of the talus can influence runoff and infiltration.

Gravel size and percent of interstitial space occupied by a fine-grained matrix are two very important sedimentologic features that influence permeability and runoff from the talus slopes. For example, the talus slopes in the Hermit Formation in upper Marble Canyon contain interstitial material derived from the shale that causes relatively low permeability ($K < 0.002$ cm/sec) and high runoff efficiency. Conversely, talus slopes composed of harder rocks, such as the Cambrian limestones at 201 Mile, form sieve deposits with high permeability ($K = 0.191$ cm/sec) and, consequently, low runoff efficiency.

The paired catchments A and E at Upper Unkar are designated as type catchments for the talus slope setting (Plate 4). The catchment areas are small, narrow, steep, and largely devoid of vegetation. The terrace sequence is narrow and drops steeply from the ap terrace to the river. Eolian dunes are common and help dissipate runoff, but they show evidence of much wind scour. The source of sand renewal has been shut off by post-dam operations, and the base of the terrace sequence appears vulnerable to potential erosion by sustained high river flows.

Debris Lobe Setting

Steep-sloped, lobate boulder deposits are commonly present at the mouths of medium-sized tributary canyons (Figure 2.3). Most of these deposits were likely deposited in middle to late Holocene time (Hereford, Burke, and Thompson 1998) and are presently incised by the main tributary canyon. Typically, small sand terrace remnants are perched on top of the debris lobe immediately below the talus or bedrock slope. Catchment areas for these deposits tend to be very small because they commonly originate a short distance upslope, either on the bedrock spur or on an old debris fan segment. These small terraces lie in a protected position outside the path of both side-canyon and river floods.

The debris lobe (or fan lobe) type setting is 122 Mile Canyon with its respective catchments B and C (Plate 5). The catchment areas at 122 Mile are very small, with little to no talus portion, and are dominated by Bright Angel Shale bedrock. Catchment B drops off the ap terrace and onto the bedrock floor of 122 Mile Canyon at the pda terrace level. Catchment C drops off the ap riser onto the 1983 separation bar.

The ap terrace remnant is relatively wide for a debris lobe setting but drops steeply with only a thin sliver of pda terrace before reaching the extensive 1983 and 1996 sand bars in the large eddy complex. The wind has blown a large amount of 1983 sand upslope against the ap terrace riser, helping to infill shallow gullies. Trailing severely exacerbates erosion of these terraces due to their steep sand slope and lack of protective vegetation.

Dune Field Setting

Wind plays an influential role in reworking sandy alluvial terraces and depositing abundant new sand in many sections of the river corridor. Locally, eolian sand accumulates as coppice dunes and is often interbedded with alluvial sand in the higher and older terraces (Figure 2.3). However, in some areas eolian deposition is the predominant surficial process and forms extensive dunes. In this case, dunes control runoff because the sand is very well sorted and highly permeable (K = 0.03 cm/s). Any gullies that do form tend to be quickly refilled with wind-blown sand. However, these areas rely on a constant supply of fresh sand from the river in order to maintain the balance of sand resupply to gullies.

The type setting at Lower Tanner with paired catchments, A and C, illustrates the dune field (or eolian) setting (Plate 6). The catchment areas are large and drain the shale-rich Dox Formation. Large alluvial fans coalesce at the base of the bedrock and talus slopes and in the mouths of local drainages. The sa terrace has been extensively reworked into a very large coppice dune complex that is well-vegetated and acts as a substantial, permeable barrier to runoff.

Alluvial fans of Dox shale have prograded into the interdunal areas of catchment A, thus locally lowering hydraulic conductivity (K=0.006 cm/s). In reducing the permeability of the eolian sand, runoff events become more concentrated through the dune complex. The gully of catchment A has progressed half the distance of the coppice dune complex. The gully of catchment C is river based and was able to break through the dune complex because of its steeper gradient to the river. Cut-and-fill structures exposed in the walls of the deep gully clearly indicate a long history of gully cutting and subsequent infilling by the river and dune sand. Eolian redistribution of river sand across and up the slope may prove to be as important for reducing rates of erosion as deposition by the river itself.

The Process-Based Conceptual Model

The process-based conceptual model describes the process-response mechanisms and relationships that control the initiation and perpetuation of gully erosion. This model is a result of intensive study at type areas and was used to evaluate the base-level hypothesis and to develop the predictive mathematical model at all study sites. Intrinsic processes and antecedent conditions ultimately drive a channel to cut across terraces to the river. Extrinsic processes also act upon the catchments to either increase or decrease erosion rates of the terraces.

The Process of Channel Initiation

Channels form from rainfall and can progress across a surface. Two general pathways cause channel formation across a flat surface of sand: overland flow and subsurface flow. Overland flow causes channels to form by two mechanisms: alluvial fan progradation, and ponding and overflow. Subsurface flow, especially if localized preferentially along a particular pathway, will cause seepage erosion and surface collapse. These processes may cause a nickpoint to migrate upslope across the terrace, eventually establishing a channel across the terrace (Higgins, Hill, and Lehre 1990). Through these mechanisms, a small ephemeral stream progressively deepens and extends its channel in the downslope direction across a series of sand terraces (Figure 3.24).

Alluvial fan progradation is a process observed in areas where the source rock in the adjacent catchment area is mostly shale (Figure 3.24A). Shale is typically very friable and produces an abundance of small, angular, pebble-sized fragments that are easily transported by flow events from the upstream talus, debris fan, or bedrock slopes. Successive storms deposit more shale clasts, causing progradation of the alluvial fan across the terrace (Hereford et al. 1993). This process establishes a slope across the flat terrace surface, which allows water to flow to the next lower terrace. Again, once water flows down the steep gradient of the terrace riser, a nickpoint forms and migrates upslope, incising the alluvial fan that produced it. Runoff then continues to incise both the alluvial fan and the terrace until it becomes graded to the next lower terrace. An example of this process can be seen at Lower Tanner Catchment A, where an alluvial fan of Dox Formation shale has prograded partly across the interdunal area of an extensive eolian complex (Plate 2).

Ponding and overflow occurs when the rate of water input onto a terrace exceeds the rate of infiltration into the terrace (Figure 3.24B). This process causes a standing body of water to form, which, when sufficiently deep, overtops the lowest point in the downstream edge of the terrace. Water pours through this low point down the relatively steep terrace riser and creates a nickpoint. As the nickpoint migrates upslope, it continues to funnel more of the ponded water. With continued runoff, the channel will eventually incise the entire terrace width and become graded to the next-lower terrace. An example is Palisades Creek, where runoff from the deeply weathered Cardenas Lava and Dox Shale have caused the deposition of clays on the broad upper ap terrace, forming an impervious playa lake bed (Hereford 1996). Other smaller scale examples are at Lower Tanner and Comanche Creek, where small ponded areas have formed during past rainfall events because a source of shale lies directly uphill.

Figure 3.24. Processes causing stream integration with the river: (A) alluvial fan progradation, (B) ponding and overflow, and (C) infiltration and piping. In all cases, a headcut forms at a terrace riser, causing nickpoint migration upslope into the higher terrace.

Infiltration and piping (seepage erosion) is caused when subsurface flow becomes localized along a particular pathway, such as large roots that extend through a terrace riser (Figure 3.24C). The water gains sufficient power to cause seepage erosion, surface collapse, and nickpoint migration across the terrace (Baker et al. 1990; Dunne 1990). Sand terraces behave like sponges to various degrees depending upon their grain-size distribution and homogeneity. Well-sorted fine to medium sand of eolian and post-dam fluvial origin has the highest permeability and homogeneity. These sands quickly absorb large quantities of runoff, reducing the ponding potential on the terrace surface.

Piping occurs when groundwater is localized along animal burrows, root cavities, layers of interbedded gravel, or channels on the underlying bedrock surface. Small sinkholes commonly form on the surface, with associated nickpoints. As a terrace becomes saturated, groundwater will flow toward its closest outlet, the terrace riser. As seepage erosion removes sand from the subsurface conduit, the terrace surface begins to sag. This sag may become an overflow point for a pond, or it may simply result in collapse. Subsequent surface collapse initiates a nickpoint that will migrate upslope from a combination of overland flow and subsurface flow. An example of infiltration and piping occurs at the type area of Nankoweap, catchments N and P (Plate 2).

Other processes of channel initiation occur outside of the catchment. These extrinsic processes include trailing and tributary overflow. Human and animal trails compact the surface and channelize water, thereby decreasing diffusivity. Tributary canyon overflow can initiate a channel where an adjacent side canyon flood event overtops its banks and flows across the terrace sequence. These events occur infrequently but can cut a large and extensive gully in a short period of time. Very clear examples are at Espejo A and B, Tanner A, and Lower Tanner D.

In summary, the establishment of an incised channel across any flat terrace is caused by headward erosion. Headward erosion begins with a nickpoint that forms in the riser of the terrace tread. The nickpoint may be generated by the leading toe of a prograding alluvial fan, by a low swale in the terrace tread, or by collapse from seepage erosion. In addition, deflation of eolian dunes and trailing may contribute to development of the subtle topographic changes that lead to gully initiation. The absence of large historical river floods, especially on higher terraces, does not allow these topographic variations to be periodically filled in or leveled out, as they were in pre-dam time. We address these processes specifically for assessment of the base-level hypothesis and for identifying anomolous sites in the predictive mathematical model.

Diffusion Capacity of the Terrace "Sponge"

A terrace sequence with greater cross sectional area will be able to absorb and diffuse more runoff than one with lesser area. Terrace cross sectional areas are calculated using depth as estimated from profile views. Sand thickness is of especially great importance in the more permeable eolian and post-dam sands because of their ability to rapidly absorb incoming runoff. The permeability of silty fine sand (pre-dam) reaches a point where the ponding rate supersedes the infiltration rate, thereby increasing the chance of overflow onto the next lower terrace.

A greater number of terraces generally creates a wider sand area and interrupts the channel-forming process due to the process described above; a terrace usually will not be incised until the terrace above it has formed a channel. Thus, the time required for a terrace-based stream to become a river-based stream is extended in direct proportion to the total width or number of all the terraces.

Well-sorted eolian sand exhibits a very high infiltration capacity and can add to the overall diffusion capacity of the terrace (Figure 3.25A). Likewise, terraces vegetated with annual grasses, forbs, and cryptobiotic crust are more resistant to channel development (Figure 3.25B). Their fine root systems and extensive ground cover disperse ponded water, slow the rate of overland flow, and increase diffusion capacity.

Eolian sand is commonly deposited on terraces and within gullies. Although the wind acts independently of runoff events in catchments, it tends to influence catchment processes. Wind can block channels from reaching the river (Plate 6) or deflate eolian dune complexes, leading to ponding and overflow (Plate 3). The repeat photos in Cataract Canyon show the annual resupply of sand to a beach with subsequent redistribution by wind into existing gullies (Figure 3.11). Likewise, the 1996 and 1983 flood sands have been blown upslope in several areas in Grand Canyon (Hereford et al. 1996; Yeatts 1998; Potochnik and Thompson, personal observations) toward draining gullies.

River processes may either deposit or erode sand from the terraces near the mouth of a catchment stream. If the river is eroding or "sapping" an embankment (Dunne 1990), the terrace sequence is narrowed, allowing an easier avenue for a small stream to reach the river. If the river is depositing sediment against an embankment, the terrace sequence is widened, reducing the ability of a small stream to reach the river. Moreover, deposition by the river fills in existing river-based gullies within its fluctuation zone (Yeatts 1996) and provides a sand source for redistribution by the wind. The ubiquitous distribution of both 1983 and 1996 post-dam flood deposits at the type catchments supports this concept (Plates 2-6).

Human mitigation includes efforts by the National Park Service and some tribes to stabilize existing terraces by using various types of rock rip-rap, wood posts, and brush and may also include re-vegetation efforts to increase the resisting framework of a terrace sequence. We do not quantify the effectiveness of these efforts, but rather use them to modify the vulnerability of a particular terrace sequence.

The Predictive Geomorphic Model

Our mathematical geomorphic model is designed to predict the erosional vulnerability of the terrace sequence where it meets the rock slopes of the catchment area. The mathematical model assumes as a starting condition that no channels cross the terraces, that is, that they are in a "pristine" state. The mathematical model includes only geomorphic factors and processes that are intrinsic to the catchment system. Extrinsic factors are described qualitatively in terms of their current or potential impact on the catchment system. Measurements of the present-day degree of degradation (as of April 1999) are used to test the mathematical model.

The three processes of gully integration—alluvial fan progradation, ponding and overflow, and infiltration and piping—are applied to the predictive mathematical model as modifying factors to the

Figure 3.25. Processes that resist erosion on terraces by increasing diffusivity: (A) increased diffusion from build-up of eolian sand, and (B) increased diffusion from grasses and organic matter covering surface.

basic model (Model 1). Model 1 relates potential runoff volume to dissipation capacity of each terrace. We then applied values for the modifying factors, called Model 2, for each terrace:

(1) Shale factor: relates the potential for alluvial fan progradation and ponding on the terrace surface, thereby reducing diffusivity
(2) Woody vegetation factor: increases the potential for seepage erosion within the terrace, thereby decreasing diffusivity
(3) Herbaceous vegetation factor: relates the potential for increasing water-holding capacity, thereby increasing diffusivity on the terrace sequence
(4) Eolian factor: relates the potential for increased infiltration, thereby increasing diffusivity

In its simplest form, the model assumes homogeneity within two types of substrate found in the terrace sequences: well-sorted sand of very high permeability (eolian and post-dam river sand) and silty fine sand of moderate permeability (pre-dam sand). For simplicity, we assume that the gravel or bedrock beneath the terraces behaves as an impermeable boundary for the movement of ground water.

Model 1 Results

Total runoff volume (Q) and peak discharge (Qp) were analyzed separately against present-day degradation (gully depth**:**total sand depth) to determine which of these factors more accurately represents the erosion-driving forces of a storm event. The relation between the two parameters shows a high correlation (R^2 = .89), where Qp is a function of Q (Figure 3.26). We choose to use Q in subsequent model development for three reasons: (1) Q is a simplifying assumption relating terrace area to total runoff volume going into that area; (2) peak discharge (Qp) is a function of total runoff volume (Q)and therefore Q should be used; and (3) runoff volume (Q) is the same unit of measure as the storage volume of terraces. A plot of Q versus present-day degradation (Figure 3.27) shows the distribution of data. The threshold line is drawn according to the deepest gully depth found at sites with the lowest vulnerability, and the line extends to the data point showing maximum gully incision at 100% vulnerability.

In Model 1, the highest terrace of each sequence is assessed for its capacity to hold water (Axt) as a function of total runoff volume (Q) from the hypothetical storm event. Therefore, terrace vulnerability (Q vul) is expressed as a ratio of Q to Axt. Figure 3.26 shows the fundamental structure of the model and the primary elements driving the system: runoff volume, Q, and terrace cross-sectional area, Axt. It should be noted that several catchments have a negative Q vul value due to the absence of upper catchment area leading into the terrace sequence. These catchments are shown in Figure 3.25 as effectively having zero vulnerability to erosion.

Points are clustered within a triangular area in the lower part of the field (Fig. 3.27), with only eight outliers above the threshold line. This line serves as a response function interpreted to represent the quasi-equilibrium effect of today's climate on the small-catchment geomorphic system. It does not account for any extrinsic factors such as influence of the dam. Points lying along the threshold line represent uppermost terraces that are close to reaching their maximum gully incision, probably as a result of these catchments being subjected to a higher number of episodic rainfall events than other catchments. Points lying along the bottom of the x-axis represent terraces not yet incised. Points lying farthest to the right have the greatest potential for erosion; points lying farther to the left have the least potential for erosion and are considered mostly stable.

If reduction in restorative processes continues, we would expect to see points shift to the right. Therefore, all points would have shifted to the right in 1963 when most of the river's sediment supply and large floods were eliminated by the closure of the dam. The loss of restorative sand increases the vulnerability (Q vul) for each site by effectively reducing the volume of the terrace "sponge."

Without restorative beach-habitat-building flows and with continued rates of erosion, we can expect that all points will steadily creep upward and toward the right. Once they reach the threshold line, maximum gully depth will be attained in a short period of time. At this point gullies will progressively widen through lateral erosion of their banks, which will eventually remove the whole terrace segment. However, if restorative processes are applied, we predict that points will slow in

Figure 3.26. Relation of two runoff parameters, peak flow (Qp) and total runoff volume (Q), as applied to the uppermost terrace at each site.

Figure 3.27. Vulnerability of top terrace versus gully depth ratio using Model 1.

their ascent and be held in stasis. With restorative floods they may even shift slightly downward and to the left, depending on the effectiveness of the restorative processes.

The position of the threshold line in Figure 3.27 is interpreted to be a function of the present climate. If storm severity and frequency increase, we predict that the threshold line will pivot upward and allow further deepening of the gullies. Conversely, if storm severity and frequency decrease, we predict that the threshold line will pivot downward and allow restorative processes to be more effective.

Model 2 Results

Model 2 is simply a refined version of Model 1 that accounts for intrinsic variations found within terraces. The presence of any of the four geomorphic factors (shale, woody plants, grasses and organic matter, and eolian sand), as discussed in Chapter 2, have been added to the vulnerability of each terrace within each study catchment. Figure 3.28 shows the Model 2 vulnerability rating of the uppermost terrace plotted against gully depth ratio. Adding the presence of these factors to each catchment results in shifting the points only slightly, thus refining the fundamental structure of the predictive model. We present the vulnerability of the uppermost terrace in this figure because that is where most of the cultural features are found in Grand Canyon. This plot shows that Axehandle Cove (catchment A) represents maximum vulnerability, with 100% of the terrace depth incised by its gully cutting through that terrace; Comanche Creek (catchment E) represents the lowest vulnerability, with 15% of its terrace depth incised by its gully.

Several extrinsic geomorphic characteristics, such as severe human impact/trailing, side canyon overflow, and the fire-hose effect from waterfalls, interfere with the predicted vulnerability of several catchments. The outlier points, which lie above the threshold line in Figure 3.26, reflect such anomalies:

Paria (B) – severe human trailing
Axehandle Cove (A, B) – firehose effect from waterfall
Espejo (A, B) – overflow channels from adjacent side canyon
Granite Park (A, F) - unknown; catchment area could extend beyond measured area
Arroyo Grande (A) – unknown; catchment area could extend beyond measured area

We also plotted Cataract Canyon catchments as a comparison to vulnerability in Grand Canyon (Figure 3.26). Most of the Cataract Canyon sites are predicted to have relatively high vulnerabilities, yet gullies have incised a maximum of 15% of the terrace depth, the same ratio as found with vulnerabilities equal to zero. We determined that processes in Cataract Canyon mimic the effects of the monsoon season in Grand Canyon. Therefore, the low occurrence of deep gullying is attributed to episodic redeposition of sand on the terrace sequence by annual floods.

Figure 3.28. Vulnerability of uppermost terrace versus gully depth ratio using Model 2, which includes geomorphic factors.

To test how effectively the model can distinguish between variations in geomorphic characteristics from terrace to terrace, and how likely a terrace will be to degrade if it receives the full impact of Q, we analyzed each individual terrace for its vulnerability to receiving the full impact of Q from the upper catchment. A frequency distribution of each measured terrace against a full range of vulnerability ratings (Figure 3.29A) shows a fairly wide and even distribution of the data. This distribution confirms that the model can detect subtle differences in geomorphic characteristics such as catchment area, type of substrate, and cross-sectional area of the terrace.

To assess a site's average vulnerability, we calculated cumulative vulnerability for each terrace at each catchment. This calculation takes into account the vulnerability of the terrace immediately upslope, assuming no degradation has occurred. In this way we can evaluate the effectiveness of the terrace "sponge" across the whole suite of terraces. These weighted average ratings are listed for each site in the Site Descriptions (Appendix B). Frequency of all terraces as calculated for cumulative vulnerability is shown in Figure 3.29B. The strong skew toward the left in the histogram shows the amount of resistance to erosion afforded by many terraces because of their protected position below more resistant higher terraces. This skew suggests that most of the terraces in Grand

Figure 3.29. Frequency distribution showing vulnerability ranges of all measured terraces: (A) terraces evaluated independently of their position within the suite of terraces, and (B) terraces evaluated dependent on their position within the suite of terraces.

Canyon are fairly protected from erosion, until the terrace above has been completely incised by a channel.

When factoring in the amount of present-day degradation to the uppermost terrace at each catchment (Figure 3.30), we find that gully depths are progressively greater with higher vulnerability classes. This histogram is simply a test of the model's predictive capability and its accuracy in representing terrace vulnerability.

Figure 3.30. Relationship of terrace vulnerability (all terraces) to gully depth ratio.

To detect trends in vulnerability throughout the canyon, values for upper terrace vulnerability are grouped according to geomorphic reach and geomorphic setting (Figure 3.31). First we wanted to see if reaches closer to the dam would show a higher average vulnerability (Figure 3.31A). This is not the case, as all reaches except the Aisles, which has substantially lower average vulnerability, show similar average vulnerability. Evidence of eolian activity is abundant at many of the sites in this particular reach, and terrace areas therefore generally tend to be larger than those in other reaches.

We then grouped average vulnerability by geomorphic setting, which separates the data more effectively (Figure 3.31B). The alluvial fan setting shows the highest average vulnerability, because catchment areas are typically highest within this setting. Likewise the tributary plain setting has large average catchment area dictating the high average vulnerability. Interestingly, catchment areas are not as strongly related to vulnerability within the talus slope and debris lobe settings. In these settings vulnerability is more a function of narrow terrace segments and therefore a relatively small

Figure 3.31. Mean vulnerability of uppermost terraces grouped by (A) geomorphic reach and (B) geomorphic setting.

terrace "sponge." The dune field setting shows the lowest average vulnerability, the result of small catchment size combined with high cross-sectional area of the terrace segment.

Integrating a Climatic Parameter into the Model

A further refinement to the model is to integrate any consistent variation in precipitation throughout the length of the Colorado River corridor. In plotting various analyses of precipitation data against elevation of weather stations located along the length of the river corridor, we detect consistently decreasing slopes in Figure 3.32 from A through C. This pattern suggests that the relationship of mean annual precipitation to elevation is strong but that of monsoon precipitation to elevation is weaker. Correlation coefficients range from 0.58 to 0.72, which indicates variable distribution in rainfall patterns progressing from the southwest to the northeast. Nonetheless, there is a general northeastward increase in annual and monsoon-season moisture.

When focusing on the Grand Canyon stations containing our study sites, from Lees Ferry to Diamond Creek, we would expect an incremental increase in moisture to the northeast, with Lees Ferry receiving the most precipitation. However, Phantom Ranch values are notably higher than those at other stations (Figure 3.32 A-C), because the orographic effect of the Kaibab-Mogollon Plateaus induces greater annual and monsoonal precipitation at this location. Values for Lees Ferry plot directly on or near the regression line and are controlled by the rain shadow effect of the K-M Plateaus. Therefore, Lees Ferry receives less annual and monsoonal precipitation than Phantom Ranch.

When frequency of rainfall events greater than 25mm/day is plotted, a strong correlation ($R^2 = 0.88$) exists between the number of large rainfall events and elevation; however, it is an inverse relationship. The number of these particular high-intensity storms increases to the southwest, probably because northerly tracking monsoon moisture in the Lower Colorado River region is not influenced by the K-M plateaus. Lees Ferry and Phantom Ranch receive a similar number of events despite their elevation difference, which attests to the influence of the K-M plateaus and the ephemeral nature of these high-intensity storms.

The strong correlation between river elevation and frequency of big monsoon storms suggests that this relation is the most useful plot of the four presented here for imposing a climatic gradient for the geomorphic model. Table 3.6 shows how data are extrapolated for each geomorphic reach using the regression equation in Figure 3.32D. This parameter is not included in the final vulnerability index but is presented in this table simply to evaluate recurrence frequency of intense storms. Future researchers can then account for the probability that Western Grand Canyon will receive more of these types of events.

Figure 3.32. Mean annual precipitations for monsoon season, in millimeters, 1967-1998: (A) mean annual precipitation; (B) mean annual precipitation for monsoon season.

Figure 3.32. Mean annual precipitations for monsoon season, in millimeters, 1967-1998:
(C) mean precipitation for peak month of monsoon season; (D) number of events >25mm/day.

Table 3.6. Climate Parameter for the Predictive Model

Reach	Length of Reach (River Miles)	Representative Catchment Location in Reach	Location of Catchment Miles from Lees Ferry	Elevation of Location (m)	>25 Ever Reac o
Cataract Canyon	12	Rapid 12	-212	1158	
Upper Marble Canyon	31	Soap Creek	12	929	
Lower Marble Canyon	31	Willy's Grave	46	859	
Furnace Flats	11	Basalt Canyon	69	807	
Aisles	18	Owl Eyes	134	594	
Western Grand Canyon	36	194 Mile Canyon	194	472	

Note: Data interpolated from the regional trend shown in Figure 3.33D for reaches examined in this study.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

Kate S. Thompson and Andre R. Potochnik

RESULTS AND CONCLUSIONS OF THE CURRENT STUDY

Results of this study indicate that the balance between catchment erosion and flood-sand deposition in Grand Canyon has been disrupted since emplacement of Glen Canyon Dam. The geomorphic response to this condition is gully rejuvenation, where down-cutting is initiated and accelerated. Also, terraces lying below cultural sites are no longer being sustained at their higher pre-dam level. The reduction of fine sediment supply (sand, silt, and clay) has propagated headward erosion at terrace risers, providing a link for gullies draining onto higher terraces to be integrated with the river. The result is increased rates of erosion on the cultural terrace through channel deepening and widening. In arriving at these conclusions, we investigated two hypotheses that might account for these changes and developed a mathematical model for predicting erosion of pre-dam terraces.

Hypotheses

The climate-variation hypothesis states that increasing intensity of rainfall has accelerated erosion processes. From an examination of previous work it appears that warm-season precipitation was more intense than average during the decades before1932, was less intense from 1932 to 1980, and has been more intense again since 1980 (Hereford et al. 1993; Hereford and Webb 1992). Previous work on winter-season rainfall shows a similar pattern of high precipitation in the first decade and last two decades of the twentieth century (Webb, Griffiths, and Melis 2000). Our conclusion from examining weather stations throughout the Colorado River system is that overall warm-season rainfall intensity did not significantly change in the 32 years before and after emplacement of the dam. Note that this comparison is based simply on the summation of the two 32-year time spans and does not take into account pulses of wet and dry periods. We cannot reject the hypothesis that increases in precipitation have caused increased gullying in the 1980s and 1990s. However, these pulses have also occurred in pre-dam time and likely were associated with arroyo cutting in that period as well, yet we do not see the evidence of such large-scale arroyo cutting in the 1965 air photos.

We also considered local variation in monsoon intensity as an explanation for the different degrees of erosion found in Cataract Canyon and Grand Canyon. The number of days that monsoon-season precipitation exceeded 25 mm from 1967 to 1998 is slightly greater in Grand Canyon than in Cataract Canyon, which could account for this difference. However, the restorative effects of annual floods probably outweigh subtle differences in precipitation patterns.

We tested the current base-level hypothesis as a possible explanation for apparent accelerated rates of erosion in archaeological river terraces of Grand Canyon. Through several lines of investigation, we concluded that the base-level hypothesis needed to include the critical role of eolian process in restoring sand to gullies and terraces. We propose the term "base-level restoration hypothesis" to incorporate the importance of periodic sand renewal to the bases of gullies and terraces. Furthermore, erosion of some sites in Grand Canyon has little relation to the presence and/or operation of Glen Canyon Dam. These sites generally show pre-dam arroyo cutting and bank retreat with little to no pre-dam annual flood deposits (pda) or 1983 sand deposits. The five sites of this type in our study are listed in Table 4.1; in the Site Description section (Appendix B) they have a "base-level hypothesis rating" of less than 3.

Table 4.1. Catchments in Grand Canyon that Do Not Support the Restorative Base-Level Hypothesis

Site	**Catchment**	**Reasons**
Axehandle Cove	A, B, C	Little evidence of pda sand; pre-dam arroyo cutting; pre-dam bank retreat
Little Nankoweap	A	Scarp retreat caused by Little Nankoweap tributary; no pda or 1983 flood sands; no eolian sand at mouth
Basalt Canyon	B	Pre-dam arroyo cutting; pre-dam scarp retreat; no pda sand
Arroyo Grande	A	Pre-dam arroyo cutting; pre-dam scarp retreat; no pda sand
Granite Park	E, F	Pre-dam scarp retreat from Granite Park Canyon; no pda or 1983 sand; no eolian sand at mouth

Studies of repeat aerial and oblique photography in Grand Canyon show that before closure of Glen Canyon Dam few gullies were incised to the degree found in 1999. Only the largest arroyos, such as those at Axehandle Cove, Tanner Canyon, Lower Unkar, and Arroyo Grande, were present in pre-dam time. Historical photos taken by Stone and La Rue in the early 1900s and repeat photography using Belknap photos of the early 1960s show that river-side sand bars were much higher and more extensive than they are today. Also, the slope at the "Old Unkar Camp," which is currently incised and exposing archaeological materials, appears in a Belknap photo to be a smooth, unincised slope with a layer of fresh eolian sand, and we found well-sorted eolian sand interbedded with silty fine sand at this locale. Presumably this slope, among many others, was periodically blanketed with fresh wind-blown sand derived from annual flood deposits in pre-dam time. We also believe that in many areas the new tamarisk riparian zone blocks eolian redistribution of flood sands to higher terrace levels. Furthermore, the dying off of mesquite in the old high-water zone has likely rejuvenated eolian deflation of archaeological sites. These hypotheses need to be further tested at each site.

Cataract Canyon served as an analogue for studying the pre-dam processes that presumably took place in Grand Canyon. The general fluvial setting and flow history of the two reaches are remarkably similar. Although terraces in Cataract Canyon are not extensive, they display a sequence that generally correlates to that in Grand Canyon. However, thorough analysis of the correlation requires some additional work.

In our studies in Cataract Canyon we found relatively little gully incision of the terrace sequence compared to that in Grand Canyon. Catchment erosion processes and geomorphic settings in Cataract Canyon are very similar to those in Grand Canyon, yet terraces appear to be more stable than those in Grand Canyon. We believe the exception is that the ratio of upper catchment runoff to the capacity of the terrace "sponge" to absorb water is greater in Cataract Canyon. One would therefore expect to see more arroyos and dissected terrace sequences in Cataract Canyon, but this is not the case, as shown by our vulnerability assessments. The highest-risk catchments in Cataract Canyon have vulnerability ratings between 50 and 65, yet none of the gullies have incised more than 20% of the terrace depth. The same range of vulnerabilities in Grand Canyon shows gullies incising up to 53% of the terrace depth (after omitting outlier catchments) with an average incision of 35% of the terrace depth.

Based on our limited two years of repeat photography at Cataract Canyon study sites, we conclude that: (1) gullies draining broad, sandy upper terraces have been mostly stable and have not been recently rejuvenated; (2) active gullies as documented in certain study areas are periodically infilled; (3) sand deposition by the annual flood tends to fill existing gullies; and (4) lower terraces in large recirculation zones are likely rebuilt every year, but channel margin bars are rebuilt less often. Therefore, the elevation and/or extent that gullies must cross to reach the river is increased periodically, perhaps at least every two years. However, this estimate needs repeat observations over a longer period of time. Finally, several instances of cut-and-fill structures were observed in arroyos in both Cataract Canyon and Grand Canyon, indicating that a dynamic equilibrium between erosion and deposition probably existed in pre-dam Grand Canyon, much like that in Cataract Canyon today.

According to our results, the climate-variation and restorative base-level hypotheses cannot be rejected. We conclude that erosion of river terraces containing archaeological resources is due to large precipitation events of the last two decades that coincide with the loss of the restorative processes of sand-bar rebuilding caused by operations of Glen Canyon Dam.

Predictive Mathematical Model and Mitigation Measures

We determined that a process-based mathematical model is the most effective way to understand the current geomorphic system and to predict which sites are most vulnerable to erosion. This type of model avoided the uncertainties that might have stemmed from short-term monitoring within the period of this two-year study. The model is connected to actual process-response relations of the geomorphic setting, and it accounts for vulnerability based on cross-sectional area of the terrace sequence and the predicted runoff volume from the upper catchment. In testing the effectiveness of this model, we concluded that catchment area is the main factor that drives gully-erosion processes and that terrace volume is the main factor that resists this erosion, through its capacity to diffuse runoff.

Vulnerability ratings were assessed with the assumption that terraces are not incised and that all are subjected to the same precipitation events. However, we compare the degree of present-day degradation of terraces with the vulnerability rating, which can be used in several ways: (1) we test the effectiveness of the model, (2) we use both vulnerability and gully-depth ratio to prioritize sites for mitigation, and (3) we establish a baseline for future monitoring of gullies. The plot of this relationship (see Figure 3.28) shows the spread of terrace vulnerability against gully-depth ratio for each study catchment and should be used as a baseline for studying rates of gully incision. Future monitors can easily measure changes in gully depth at our pre-established points of measurement, track how points shift on this scatter plot, and evaluate the rates at which a terrace is degrading or aggrading.

The highest-priority sites are summarized in Table 4.2, along with gully-depth ratios. High vulnerability ratings and gully-depth ratios greater than 0.5 indicate that a catchment has already incised most of its terrace depth and that mitigation efforts should therefore focus on data recovery. Sites with high vulnerability ratings and gully-depth ratios less than 0.5 are good targets for checkdams and/or diversion bars. Generally, any mitigative action such as placement of checkdams should be focused at the talus slope/sand terrace interface; such efforts are already ongoing at 122 Mile, catchment A. Since catchment area is such a dominant component driving gully erosion, efforts should be concentrated on increasing diffusion capacity of the terrace by slowing water from the upper catchment, or even diverting water away from the cultural site of concern. We observed mitigative structures at many sites within Grand Canyon, but in only a few places are efforts concentrated at the talus/terrace interface. Of further note is the need to concentrate water in one channel. If diversion structures are used, efforts to channelize water are imperative to prevent multiple gullies from forming. Individual site vulnerability ratings are listed with the Site Descriptions in Appendix B; air photos of catchment locations are provided in Appendix D. We recommend that these appendixes be used in the field to guide monitors and managers in prioritizing sites for remedial action.

Gully erosion processes and river processes can be generalized for each type of geomorphic setting. Generally, alluvial fan, tributary plain, and talus slope settings show the highest vulnerability ratings. The catchment areas in alluvial fan and tributary plain settings are typically very large, whereas terrace volumes are very small in the talus slope settings despite typically small catchment size. Dune field settings are the least vulnerable to erosion because they typically have smaller catchment areas and large areas of sand with high diffusion capacity. Debris lobe settings and talus slope settings typically show moderate vulnerability to erosion because upper catchment areas are of relatively small size, and terrace segments tend to be narrow. We suggest that all archaeological monitoring sites be grouped according to geomorphic setting to improve predictions about site vulnerability. The predominant geomorphic setting is listed for each site in Appendix B.

Table 4.2. Ranking of Highest-Risk Sites Based on Vulnerability Rating of Top Terrace

Site	**Catchment**	**Vulnerability of Top Terrace**	**Gully-Depth Ratio[1]**
Axehandle Cove2	A	100	1.00
Nankoweap	N	88	0.11
Palisades	B	88	0.35
Nankoweap	P	75	0.32
Axe Handle Cove	C	74	0.03
Palisades[2]	B'	72	0.57
Comanche Creek[2]	H	71	0.55
Comanche Creek	F	70	0.25
Lava/Chuar	A	69	0.07
209 Mile	A	69	0.19
196 Mile	A	67	0.02
209 Mile	B	67	0.42
Lower Tanner	F	66	0.19
Kwagunt	A	66	0.40
Palisades	H'	65	0.08
Nankoweap	K	65	0.23
Nankoweap	V	64	0.06
Soap Creek	C	62	0.03
Soap Creek	A	62	0.37
201 Mile	A	59	0.30
Arroyo Grande[2]	A	59	1.00

Nankoweap	O	58	0.09

[1]Included to identify sites where data recovery is recommended.
[2]Gully at this site has incised over half of the terrace depth; site should be mitigated through a data recovery program.

Restorative efforts should be directed toward replenishing sand to lower terraces. Our results show that wind is an important mechanism, transporting sand to upper terrace risers and periodically infilling gullies. Currently dunes are being depleted because of a lack of new source material. Periodic replenishment of sand by beach-habitat-building flows (BHBFs) is the most viable and efficient means of sustaining the terrace "sponge," a concept discussed in Chapter 2 and Chapter 3. Presence or absence of the post-dam1983 and 1996 flood sands as well as the most recent pre-dam terrace (pda) at individual sites is included in the site descriptions (Appendix B). Presence of these flood deposits offers clues for implementing future BHBFs as part of Adaptive Management in Grand Canyon. These flows should be greater than 45,000 cfs, up to a maximum of 120,000 cfs, given adequate sediment storage in the river. We selected this maximum based on a recurring flood level since the 1921 flood. The flood of 1957 was estimated at 126,000 cfs, which was the last big flood before closure of Glen Canyon Dam. Floods of this nature should be planned as close to main-tributary flooding as possible to prevent mining of the Colorado River channel (Kaplinski et al. 1999). Furthermore, based on our infiltration results, well-sorted sand of the post-dam era is very effective at diffusing runoff and behaves much like eolian sand. In spite of the lack of silt and clay, we believe that the 1983 sand is one of the most effective terraces in resisting erosion because of its high diffusion potential, more so than pre-dam sand. It is fairly homogeneous and permeable and behaves as a sponge in the mouths of existing arroyos and at the base of higher pre-dam terraces.

Cataract Canyon should be considered as a potential study area for conceptualizing BHBF scenarios in Grand Canyon because of the similarities between the two in geomorphic setting, flow history, and hydrologic features. Through periodic topographic surveys of beaches in Cataract Canyon, researchers can predict, to some degree, areas of deposition and erosion from a particular flood, given a known sediment load. This model could perhaps be projected for Grand Canyon, given its restricted sediment load. Case scenarios of annual floods in Cataract Canyon provide opportunities for experimentation that may be too risky in Grand Canyon. Implementation of this recommendation would greatly reduce costs associated with "test flood flows" in Grand Canyon. BHBFs should be regularly used as a management tool to curtail accelerated erosion of cultural sites.

Photogrammetrically produced topographic maps for each type of geomorphic setting provide a possible means of monitoring gullies and obtaining gully erosion rates without conducting in-field surveys. In checking resolution levels of these maps, we found that most of the topography is accurately represented by 25-cm contour intervals (field check observations by Andre Potochnik). However, a few areas show that the digital model probably extrapolates 25-cm contours between 1-m contours, thus concealing any subtle topographical changes. The resolution of these maps needs further improvement before they can be used for monitoring. Testing for accuracy of this method might require digitally reproducing an area twice from the same air photo and checking contours to make sure they match exactly. It is imperative to find out whether changes measured from these maps are real or just an artifact of map inaccuracy.

Archaeological monitoring of sites in sandy deposits should be based on a geomorphic monitoring program. Such a program would include quantitative monitoring of river terraces and dunes that could contain cultural sites and features. We propose a modification to the current River Corridor Monitoring Program (RCMP) to include simple repeat measurements at each catchment and/or photogrammetric-style repeat mapping to avoid extensive field work and the resultant impacts to sites. The work conducted thus far on the large sample set of sites should be expanded to include the remaining sites located in sandy deposits.

RECOMMENDATIONS FOR FUTURE WORK

The most immediate concerns for future work regard the predictive model. To refine its predictive capability, we suggest the following:

(1) Improve accuracy of gully depth ratio measurements. Sand depth down to gravel or bedrock was measured if cross-sectional view was available at a site. Many sand depths had to be estimated at sites if no cross section could be measured. Technology such as ground-penetrating radar could be used to improve this parameter of the model.

(2) Improve accuracy of morphometric measurements. Once GCMRC has obtained orthophotos for all archaeological sites in the RCMP, then catchment areas and stream lengths can be accurately calculated for all sites..

(3) Incorporate upper catchment slope and terrace slope into the predictive model. Qp would then be recalculated and applied to the upper terrace, and vulnerabilities would be recalculated accordingly.

(4) Incorporate work at type catchment areas with S. M. Wiele's work in progress on modeling of potential flood-deposited sand at areas with archaeological materials. To fully understand restorative base-level processes, a one-dimensional flow model should be projected in catchments to predict amount of channel aggradation in gullies.

Other work would involve a thorough test of the hypotheses presented in this paper, including the following:

(1) Determine extent of arroyo cutting in pre-dam time by conducting a repeat photography study using historic photos. This study should also include photos that further test the restorative base-level hypothesis.

(2) Climate re-analysis. Precipitation records at related stations throughout the southern Colorado Plateau need to be analyzed as a time series using daily precipitation records. Analyses could then account for antecedent soil moisture conditions from previous daily precipitation. A climatologist should undertake this type of study.

(3) Determine where historical floods could have overtopped prehistoric terraces. Preliminary investigation at Palisades Creek and Arroyo Grande show that the ap unit was overtopped by floods in the 1800s or perhaps by the flood of 1921. It is possible that many archaeological sites were periodically covered by high-magnitude historical floods that kept these resources buried and protected from accelerated erosion.

(4) Study process of eolian deposition or erosion around sites. Develop a thorough understanding of how eolian processes relate to the reduction of annual flooding and sediment supply caused by Glen Canyon Dam.

DEVELOPMENT OF A GEOMORPHIC MODEL TO PREDICT EROSION OF PRE-DAM COLORADO RIVER TERRACES CONTAINING ARCHAEOLOGICAL RESOURCES

Prepared for

GRAND CANYON MONITORING AND RESEARCH CENTER

Submitted by

SWCA, INC.
Environmental Consultants

February 18, 2000

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BOR Cooperative Agreement No. 1425-98-FC-40-22610

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APPENDIX A

DATA SHEETS

Catchment Data Sheet

Date: ________ Time:__________ Weather:______________________

Workers: __________________________________

Catchment location____

RM/side:________ Catchment#_______ Arch Site #__________________

Geologic fm. (s):_______________________________

River-based? Y N Terrace-based on ________________________terrace.

Catchment area (est.): S M L (sketch thalweg and area boundary on map base)

Map base: air ph. archeo. GIS Herf. Ivo L.

Hdwter geomrph: Debris fan Talus Eolian: active inactive Bedrock

Slope aspect:_________

Rock material at mouth: sand gravel bedrck other ___________

terraces present	cum. hght. from 45k (m)	width (m)	grain size (cl/si/sa)	arroyo (m) dpth/wdth	nickpts. (m)	sand depth (m)	human impact sl/md/sv
45k							
100k							
pda							
lmt							
umt							
ap							
sa							

Height (45k-top terr.):________ Distance (45k to top terr.) ________ Slope:________

Process of channelization ________________

Notes:

PO = ponding and overflow
_____ thin clay/silt layers on terrace
_____ impervious sediment on terrace
_____ "pour-offs" on terrace risers

AF = alluvial fan progradation
_____ build-out of pebbly gravel
_____ shale source in catchmnt above

IP = infiltration and piping
_____ burrows/roots in terrace riser
_____ nickpts. formed by piping
_____ very shallow sand depth

Data of Line-Intercept Ground Surface Sampling (m)

Location: **Date:**

Terrace

	Woody	Herb	Crypto	Rock	Bare
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
Sum					

Terrace

	Woody	Herb	Crypto	Rock	Bare
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
Sum					

Terrace

	Woody	Herb	Crypto	Rock	Bare
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
Sum					

Terrace

	Woody	Herb	Crypto	Rock	Bare
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
Sum					

APPENDIX B

SITE DESCRIPTIONS AND VULNERABILITY RATINGS

APPENDIX B

SITE DESCRIPTIONS AND VULNERABILITY RATINGS

DEFINITION OF TERMS

The geomorphic setting describes the foundation in which a catchment in the terrace portion has developed. Five geomorphic settings are defined: alluvial fan, tributary plain, talus slope, debris lobe, and dune field. One predominant setting is listed for each site.

The base level of a stream is the longitudinal profile below which a stream cannot degrade. The term is used here as the level of sand-bar rebuilding of the Colorado River.

The process of channel integration refers to how the channel found its way from the upper catchment to the sandy terraces and how it is trying to reach the river. Three main processes (described in detail in Chapter 2) summarize how a channel can become integrated with the river: (1) ponding and overflow, (2) alluvial fan progradation, and (3) infiltration and piping. These processes result in headcut development and nickpoint migration (discussed in Chapter 1). Other minor processes, such as human trailing or scarp retreat from past river floods, are noted where they apply.

The condition of the pre-dam alluvium (pda) represents the resilience of river flood deposits from the time just before emplacement of Glen Canyon Dam to the present.

The strength of the base-level hypothesis evaluates the degree to which each site supports or negates the current driving hypothesis. Sites are rated from 1 to 5 by assessing certain processes and geologic units present (discussed in Chapter 2). A rating of 5 shows full support for the base-level hypothesis; a rating of 1 negates this hypothesis. Any rating of 3.0 or less indicates that erosion is probably happening due to factors unrelated to the dam or its operations (see Table 2.2).

River characteristics are the types of recirculation zones or cutbanks that exist at river level in the area where the channel would debouch. Since characteristics change with stage height, we refer to two primary flow regimes: (1) Power Plant Capacity (PPC), flows up to 32,500 cfs; and (2) high flows, referring to post-dam flood flows of 1983 and 1996. For some sites we refer to 60,000 cfs as the threshold for significant deposition when 1983 sand is present but 1996 sand is not.

The potential benefit of a restorative flood flow describes the setting for potential deposition or erosion based on the presence (or absence) and extent of the 1983 and 1996 sand deposits.

The vulnerability rating was generated from a series of mathematical equations that are mostly a function of catchment area and type of substrate. Details about how the vulnerability rating was formulated can be found in Chapter 2. This rating is the final representation of the degree to which the site is at risk and is based on a 1-100 scale, with 1 indicating lowest risk and 100 indicating highest risk.

Copies of air photos showing catchments are provided in Appendix C to assist in assessing sites.

SITE DESCRIPTIONS

SITE: PARIA RIVER EDDY (Catchments A, B)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Trails, steep sand slope, narrow sand width, high percent bare ground.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: A and B are distributary streams originating from the same catchment area. Upslope trail in the 1983 and pda levels causes gully entrenchment in A. Human trailing on pda riser is primary cause of channel integration across terrace sequence. Infiltration and piping from animal burrows also occurs. Both processes have induced nickpoint migration in the upper terraces.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda terrace is thickly vegetated with saplings of willow and tamarisk, but trails result in gully entrenchment across terraces.
RIVER PROCESSES: PPC flows - separation bar with abundant deposition in a large eddy; High flows - recirculation zone with separation and reattachment bar.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Both 1983 and 1996 flood sands are abundant; high potential for flood sand to infill gully mouths and build up base level at mouths; this should slow further erosion of the pda terrace.

Average Vulnerability of Terraces: A = 20, B = 9
Vulnerability of Top Terrace: A = 52, B = 32

SITE: AXEHANDLE COVE (Catchments A, B, C)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area, steep sand slope, few terrace levels, overhanging bedrock portion of catchment.
BASE LEVEL OF CHANNEL: 1983 deposit.
PROCESS OF CHANNEL INTEGRATION: Big arroyos caused by water falling from overhanging cliff directly onto ap terrace; nickpoint migration and channel widening and deepening are a result of scarp retreat and piping within the channel; alluvial fan progradation on 1983 deposit will enable channel to reach river.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Only a few pda remnants still present; evidence that pda has been eroded away, probably by a pre-dam flood event.
RIVER PROCESSES: PPC flows - point bar setting. High flows - channel margin bar; small extent of 1983 sand indicates a very small recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 2.0; arroyo development in pre-dam time; pda not extensive; bank retreat from pre-dam floods; no eolian reworking.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Extent of 1983 and 1996 sands minimal; minimally restorative with flow levels above 45,000 cfs.

Average Vulnerability of Terraces: A= 90, B = 17, C = 73
Vulnerability of Top Terrace: A = 100, B = 24, C = 74
Anomalies: firehose effect from waterfall

SITE: TEN MILE ROCK (Catchment A)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Narrow sand width, high percent bare ground.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow on terraces; nickpoint migration in channels due to overflow off terrace risers.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Partly covered by windblown 1983 sand; extensive, narrow deposit incised by small gullies.
RIVER PROCESSES: PPC flows - channel margin bar setting; High flows - recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties present.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: 1983 and 1996 flood sands indicate favorable conditions; high potential for flood sand to infill gully mouths and build up base level at mouths; this should slow further erosion of the pda terrace.

Average Vulnerability of Terraces: A = 8
Vulnerability of Top Terrace: A = 22

SITE: SOAP CREEK (Catchments A, B)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area, high percent bare ground.
BASE LEVEL OF CHANNEL: 1983 terrace for A, B; mt terrace for C.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation present on terraces; nickpoint migration causes deepening and widening of arroyos. 1983 deposit prevents catchments A, B from reaching river.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda is preserved only at the downstream end of the terrace area.
RIVER PROCESSES: PPC flows - upper pool recirculation zone; High flows - upper pool recirculation area probably becomes a large depositional zone at flows around 100,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.00; all base-level properties present, except that pda is not extensive.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW. Flows need to be well above 45,000 cfs for arroyo mouths to be infilled and for significant deposition.

Average Vulnerability of Terraces: A= 52, B = 43
Vulnerability of Top Terrace: A = 62, B = 55

SITE: SOAP CREEK (Catchment C)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area, high percent bare ground.
BASE LEVEL OF CHANNEL: Mt terrace in side canyon.
PROCESS OF CHANNEL INTEGRATION: Nickpoint migration causes deepening and widening of gully.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Deposit is present both in the side canyon and as part of the terrace sequence; it is unincised near Catchment C.
RIVER PROCESSES: PPC flows - upper pool recirculation zone; High flows - upper pool recirculation area probably becomes a large depositional zone at flows around 100,000 cfs.

STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; site occurs at outside bend of side canyon where erosion has caused bank retreat; pda and 1983 deposits do not help slow nickpoint migration because of their location relative to the mouth of Catchment C; eolian reworking main benefit to site.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: This site would not benefit directly from a flood flow because the gully debouches into the side canyon well above the area of potential effect. However, eolian reworking of new flood sand would benefit this site

Average Vulnerability of Terraces: C = 57
Vulnerability of Top Terrace: C = 62
Anomalies: side canyon-based stream

SITE: WILLY'S GRAVE

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Trails across slope.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Trails leading to the grave site have directed runoff into two small, relatively inactive channels. NPS rerouting of the trail has slowed active downcutting. Alluvial fan progradation noted on terraces; ponding and overflow also present.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda is well preserved and relatively unincised; appears to buttress higher sand deposits.
RIVER PROCESSES: PPC flows - large upper pool recirculation zone; High flows - huge upper pool recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0. All base-level properties present
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Large volumes of 1983 and 1996 flood sand; high potential for flood sand to infill gully mouths and build up base level at mouths; this should slow further erosion of the pda terrace.

Average Vulnerability of Terraces: A = 8
Vulnerability of Top Terrace: A = 23
Anomalies: trailing partly forms gully

SITE: LITTLE NANKOWEAP (Catchment A)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Bedrock slope, bank retreat from side canyon.
BASE LEVEL OF CHANNEL: Umt terrace.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow create headcuts off terrace risers; nickpoint migration in the ap and sa terraces causes slight channel deepening.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda is not present; it may have been eroded away by Little Nankoweap Creek floods.
RIVER PROCESSES: PPC flows - upper pool deposit; High flows - upper pool deposit; at 100,000 cfs, water would overtop the debris fan and deposit sand as a channel margin deposit.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 2.0; lack of 1983 and pda deposits, bank retreat due to side-canyon erosion; no evidence of reworked flood sand by wind.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Extent of 1983 and 1996 deposits is minimal, although they occur as thick deposits just upstream. However, flood sand would infill bouldery debris fans, replenishing some sand to lower terrace levels.

Average Vulnerability of Terraces: A = 18
Vulnerability of Top Terrace: A = 39
Anomalies: scarp retreat from tributary

SITE: LITTLE NANKOWEAP (Catchments B-E)

GEOMORPHIC SETTING: Dune field
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope. high percent bare ground.
BASE LEVEL OF CHANNEL: Debris lobe dunes at mt level.
PROCESS OF CHANNEL INTEGRATION: Wind deflation has created swales; infiltration and piping has created small channels.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present because deposits have been reworked into active dunes.
RIVER PROCESSES: PPC flows – channel margin deposits; High flows – channel margin deposits that will likely be reworked by the wind.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0: pda deposit has been reworked into dune: active eolian effect maintains high base level.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: 1983 and 1996 deposits pinch in and out here: sand will be deposited but will probably be subsequently reworked by wind benefiting the upper terraces.

Average Vulnerability of Terraces: B, C, D, E = 0
Vulnerability of Top Terrace: B, C, D, E = 0
Anomalies: eolian healing effect

SITE: NANKOWEAP (Catchment F)

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: None; strong eolian restorative force here.
BASE LEVEL OF CHANNEL: Pda terrace.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties present.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow; eolian dunes entrap and pond water but prevent erosive overflow channels from downcutting into the sand.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda is a thick deposit, is well-vegetated, and is relatively undissected.
RIVER PROCESSES: PPC flows – channel margin bar that is mostly gravel; High flows – the higher the flow the more sand will likely be deposited as an upper pool deposit.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: The presence of 1983 and 1996 sands indicates a depositional zone.

Average Vulnerability of Terraces: F = 20
Vulnerability of Top Terrace: F = 48
Anomalies: eolian healing effect

SITE: NANKOWEAP (Catchments G-I; J eliminated)

GEOMORPHIC SETTING: Dune field
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope: active eolian is big restorative force.

BASE LEVEL OF CHANNEL: Lmt terrace (recently covered with eolian sand).
PROCESS OF CHANNEL INTEGRATION: Wind deflation initially formed swale; infiltration and piping has developed small channels.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present here; occurs just upstream and downstream of this area, where deposit remains unincised.
RIVER PROCESSES: PPC flows - channel margin bar that is mostly gravel; High flows - the higher the flow the more sand will likely be deposited in a recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties present.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: The presence of 1983 sands nearby indicates a potential depositional zone at flows above 50,000 cfs; the 1983 deposits were likely stripped off by the high flows of 1984, 1985, and 1986.

Average Vulnerability of Terraces: G, H, I = 0
Vulnerability of Top Terrace: G , H, I = 0
Anomalies: eolian healing effect

SITE: NANKOWEAP (Catchment K)

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area.
BASE LEVEL OF CHANNEL: Pda terrace level.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping are likely due to abundance of roots.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Thin segment of pda terrace here, but it is not incised.
RIVER PROCESSES: PPC flows - channel margin bar setting, but very little sand indicates active erosion caused by current flow regime; High flows - presence of small 1996 deposit and lack of 1983 deposit suggest a channel margin depositional zone from 45,000 cfs to about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no significant 1983 flood sand present; 1983 level expressed as gravel and driftwood.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Only small benefit from a flood flow above 45,000 cfs; however, area would not be adversely impacted.

Average Vulnerability of Terraces: K = 65
Vulnerability of Top Terrace: K = 65
Anomalies: very wide and low angle sand portion; thickly vegetated with mesquite

SITE: NANKOWEAP (Catchment L)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Steep bedrock slope and narrow width of sandy portion of terrace sequence.
BASE LEVEL OF CHANNEL: Lmt terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progrades onto pda level; human trailing localizes runoff and causes nickpoints to form. Debris lobe sand at pda level slows further downcutting, as does great distance to the river across gravel terrace.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Presently mounded into eolian sand dune; dune blocks mouth of channel trying to push its way to the river.

RIVER PROCESSES: PPC flows - channel margin bar that spans very wide cobble bar; High flows - no 1996 or 1983 flood sands present, which suggests little deposition from a flood flow; however, no adverse impacts would occur.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no significant 1983 flood sand present; 1983 level expressed as gravel and driftwood.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: No benefit immediately below mouth of this channel; however, deposition would likely occur on the down-river side of the high ridge, as a recirculation zone forms at stage levels above 45,000 cfs.

Average Vulnerability of Terraces: L = 27
Vulnerability of Top Terrace: L = 44
Anomalies: huge gravel bar and eolian deposits inhibit stream from reaching river

SITE: LOWER NANKOWEAP (Catchments N-P; M eliminated)

GEOMORPHIC SETTING: Alluvial fan
PRINCIPLE FACTORS DRIVING EROSION: Steep bedrock slope; steep sand slope; short distance to river.
BASE LEVEL OF CHANNEL: Lmt terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping is predominant process; many animal burrows and root cavities present in ap terrace riser; small alluvial fan forms on lmt terrace.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): A narrow yet extensive terrace here; alluvial fans form on this level, and it has not yet been dissected.
RIVER PROCESSES: PPC flows - reattachment bar. High flows - very large recirculation zone forms site for large amount of deposition; 1983 reattachment bar forms main camp for river runners.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Large expanse of 1983 sand and presence of 1996 sand indicate site of significant deposition.

Average Vulnerability of Terraces: N = 87, O = 0, P = 72
Vulnerability of Top Terrace: N = 88, 0 = 58, P = 75

SITE: LOWER NANKOWEAP (Catchment Q)

GEOMORPHIC SETTING: Alluvial fan
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area; steep sand slope; steep bedrock slope.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping are the dominant processes; Lmt terrace riser is cut by two revegetated trails.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): A narrow yet extensive terrace that has alluvial fan but still remains unincised.
RIVER PROCESSES: PPC flows - reattachment bar. High flows - very large recirculation zone forms site for large amount of deposition; 1983 reattachment bar forms main camp for river runners.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Large expanse of 1983 sand and presence of 1996 sand indicate site of significant deposition.

Average Vulnerability of Terraces: Q = 10

Vulnerability of Top Terrace: Q = 0

SITE: LOWER NANKOWEAP (Catchment R; S eliminated)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep bedrock slope.
BASE LEVEL OF CHANNEL: Lmt terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping are the dominant processes; Lmt terrace riser is cut by two revegetated trails.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): A narrow yet extensive terrace that has alluvial fan but still remains unincised.
RIVER PROCESSES: PPC flows – reattachment bar. High flows – very large recirculation zone forms site for large amount of deposition; 1983 reattachment bar forms main camp for river runners.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Large expanse of 1983 sand and presence of 1996 sand indicate site of significant deposition.

Average Vulnerability of Terraces: R = 22
Vulnerability of Top Terrace: R = 38
Anomalies: mostly stable due to low gradient and mature vegetation

SITE: LOWER NANKOWEAP (Catchment V; T and U eliminated)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Steep bedrock and sand slopes; narrow sand width.
BASE LEVEL OF CHANNEL: Lmt terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping are predominant processes: some ponding and overflow off the terrace riser has created a deep headcut.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Narrow deposit that is still unincised.
RIVER PROCESSES: PPC flows – reattachment bar. High flows – channel margin deposit; narrow pda and 1983 deposits suggest possible scarp retreat during flood flows.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except that area depicts scarp retreat (probably during high flows).
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Very narrow strip of 1983 sand and no 1996 sand suggest little benefit from a flood flow.

Average Vulnerability of Terraces: V= 37
Vulnerability of Top Terrace: V = 64

SITE: KWAGUNT (Catchment A)

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: Moderately large catchment area.
BASE LEVEL OF CHANNEL: Mt terrace.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow are predominant processes; some infiltration and piping evident; eolian dune creates barrier near mouth of channel.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda level comprised of gravel with little sand.
RIVER PROCESSES: PPC flows - separation bar. High flows - separation and reattachment bar serves as locus for sand deposition.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no pda sand present here.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 and 1983 deposits indicates good depositional area.

Average Vulnerability of Terraces: A = 51
Vulnerability of Top Terrace: A = 66
Anomalies: low gradient slope and eolian dunes keep area stable

SITE: 60 MILE CANYON (Catchments A, B)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope of ap riser.
BASE LEVEL OF CHANNEL: 1983 level.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation; nickpoint migration mostly caused by pour-offs from ap riser onto lmt terrace; human trail leading upslope helped channelize gully.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): A small area of pda exists with much driftwood; a small alluvial fan has formed on pda, but otherwise it is not incised.
RIVER PROCESSES: PPC flows - channel margin deposit; High flows - upper pool deposit with good-sized recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; 1983 level is mostly gravel; side canyon has eroded escarpment of ap deposit.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: 1996 flood sand present, but 1983 sand is minimal. Flood flows above 45,000 cfs may not deposit sand, but will not harm higher terraces either.

Average Vulnerability of Terraces: A = 22, B = 16
Vulnerability of Top Terrace: A = 28, B = 24
Anomalies: side canyon influence and very steep and high ap/dune riser.

SITE: LAVA CANYON (Catchment A)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope; narrow width of sandy terraces; human trailing.
BASE LEVEL OF CHANNEL: Lmt terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation; human trailing has increased erosion along this channel; however, mitigation has arrested erosion at this time.

CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present.
RIVER PROCESSES: PPC flows - channel margin deposit; High flows - channel margin deposit at flows less than 100,000 cfs (no 1996 or 1983 sand here); upper pool deposit at flows greater than 225,000 cfs (no pda deposit here, only lmt and umt).
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; no 1983 or pda sand here; no eolian reworking..
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1996 and 1983 flood sands suggests minimal benefit; however, gravel deposits at 1983 level suggest that site will be protected from erosion of flood flows.

Average Vulnerability of Terraces: A = 64
Vulnerability of Top Terrace: A = 69
Anomalies: major revegetation and stabilization efforts now make this gully somewhat stable

SITE: LAVA CANYON (Catchment B)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: High percent bare ground; severe human trailing.
BASE LEVEL OF CHANNEL: 1983 level.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation (1983 sand has been blown up onto the alluvial fan and up onto lmt riser, maintaining base level at 1983 level); human trailing has increased erosion along this channel; however, recent mitigation has temporarily arrested erosion.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present.
RIVER PROCESSES: PPC flows - channel margin deposit; High flows - channel margin deposit at flows less than about 60,000 cfs (no 1996 sand here); upper pool deposit at flows greater than 60,000 cfs and less than 225,000 cfs (1983 sand has been blown up onto lmt riser, leaving a gravel deposit at 1983 level; no pda deposit here).
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; minimal 1983 sand and no pda sand here.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1996 deposit here; however, 1983 flood sand once existed and has been removed. This suggests a beneficial flood flow of at least 60,000 cfs.

Average Vulnerability of Terraces: B = 26
Vulnerability of Top Terrace: B = 41
Anomalies: major revegetation and stabilization efforts now make this gully somewhat stable

SITE: PALISADES CANYON (Catchment A)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Steep bedrock slope.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation is dominant process; infiltration and piping also contributes to nickpoint development (*Note:* Beamer trail crosses all of these channels but does not exacerbate gully development).
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive terrace; not yet incised.
RIVER PROCESSES: PPC flows - reattachment bar; High flows - large recirculation zone with separation and reattachment bar.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.

POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Only minimal 1996 sand present, but thick 1983 deposits extend throughout area; indicates deposition with flows above 45,000 cfs.

Average Vulnerability of Terraces: A = 42
Vulnerability of Top Terrace: A = 51
Anomalies: very thick mesquite bosque at pda level

SITE: PALISADES CREEK (B'-D)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Periodic overflow from Palisades Creek.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Drainages originated as part of old debris channels that broke through from Palisades Creek from the 1890s to the 1930s (Hereford 1996). Infiltration and piping are evident in the sandy terraces, contributing to nickpoint migration (*Note:* Beamer trail crosses all of these channels but does not exacerbate gully development).
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive terrace here; terrace still unincised at the mouths of these drainages.
RIVER PROCESSES: PPC flows - reattachment bar; High flows - large recirculation zone with separation and reattachment bar deposits; lack of 1996 deposits here suggests that deposition occurs above 45,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; these channels were periodically affected by overflow from Palisades Creek; all other base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Absence of 1996 deposit and extensive, thick 1983 deposits indicate beneficial flows above 45,000 cfs.

Average Vulnerability of Terraces: B = 81, B' = 66, C = 19, D = 8
Vulnerability of Top Terrace: B = 88, B' = 72, C = 33, D = 18
Anomalies: overflow channels from Palisades Creek

SITE: PALISADES CREEK (Catchment E)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Narrow width of sandy terraces; possible overflow channel from Palisades Creek.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping are dominant processes in sandy terraces; possible that channel originated from overflow of Palisades Creek; alluvial fan progradation probably linked upper gravel portion to lower sandy portion of channel (*Note:* Beamer trail crosses this channel but does not exacerbate gully development).
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present here.
RIVER PROCESSES: PPC flows - channel margin deposit; High flows - upper pool deposit; presence of 1996 and 1983 deposits suggests that deposition occurs above PPC flows.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except that drainage could be influenced by overflow from Palisades Creek.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 sand and thick 1983 deposit indicate deposition above PPC flows.

Average Vulnerability of Terraces: E = 30

Vulnerability of Top Terrace: E = 46
Anomalies: possible overflow channel from Palisades Creek, which would cause large headcuts

SITE: PALISADES CREEK (Catchments F, G)

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: Narrow width of sandy terraces; heads of these two channels lie very close to larger drainage that heads in Palisades fan.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation on sandy terraces; ponding and overflow also evident; this process can potentially result in capture of the larger drainage, which would significantly deepen and widen these channels.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): A gravel deposit forms the pda level here; just downstream the deposit has been reworked into dunes.
RIVER PROCESSES: PPC flows - separation bar; High flows - separation and reattachment bar; presence of 1996 and 1983 deposits indicate a depositional zone here.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; mostly gravel deposit at pda level; little sand.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: This area forms a recirculation zone at flood flow levels; presence of 1996 and 1983 sand suggests that deposition would occur at levels above PPC flows.

Average Vulnerability of Terraces: F = 19, G = 0
Vulnerability of Top Terrace: F = 33, G = 2
Anomalies: extremely vulnerable due to proximity to trail and potential stream capture

SITE: PALISADES CANYON (H)

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: very large catchment area; human trailing and camping.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow from playa are main processes of channel entrenchment; alluvial fan progradation probably caused catchment to become river based; extensive eolian dunes and coppice dunes previously separated playa and drainage from river; coppice dunes appear to be eroding laterally, as evidenced by exposed tree roots; eolian dunes cannibalized by lack of fresh river flood sand.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Very wide and still well preserved here; river sand (?) deposited on the floor of the old cabin (mapped as ap by Hereford) could indicate that pre-dam flood reached this level in late 1800s.
RIVER PROCESSES: PPC flows - separation and reattachment bar; High flows - separation and reattachment bar; presence of 1996 and 1983 deposits indicates a depositional zone here.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist (*Note:* locality used by Hereford and others [1993] to describe base-level hypothesis).
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: This area forms a recirculation zone at flood flow levels; presence of 1996 and 1983 sand suggests that deposition would occur at levels above PPC flows.

Average Vulnerability of Terraces: H = 64
Vulnerability of Top Terrace: H = 79

Anomalies: playa creates huge ponding and overflow for one arm; debris flow channels feed another arm; huge catchment size; coppice dunes breached by arroyo

SITE: PALISADES CANYON (H')

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: large catchment area; human trailing and camping.
BASE LEVEL OF CHANNEL: pda
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow from playa are main processes of channel entrenchment; extensive eolian dunes and coppice dunes previously separated playa; coppice dunes appear to be eroding laterally, as evidenced by exposed tree roots; eolian dunes cannibalized by lack of fresh river flood sand.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Very wide and still well preserved here.
RIVER PROCESSES: PPC flows – separation and reattachment bar; High flows – separation and reattachment bar; presence of 1996 and 1983 deposits indicates a depositional zone here.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist (*Note:* locality used by Hereford and others [1993] to describe base-level hypothesis).
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: This area forms a recirculation zone at flood flow levels; presence of 1996 and 1983 sand suggests that deposition would occur at levels above PPC flows.

Average Vulnerability of Terraces: H' = 50
Vulnerability of Top Terrace: H' = 65
Anomalies: playa creates huge ponding and overflow potential; coppice dunes recently breached by gully

SITE: ESPEJO CREEK (Catchments A, B)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Overflow from Espejo Creek; high percent bare ground.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation is main process on pda and 1983 terraces; arroyos initiated when Espejo Creek overflowed its banks in pre-dam time; infiltration and piping aids in nickpoint development.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda sand is dissected by these deep arroyos.
RIVER PROCESSES: PPC flows – separation bar created by channel on left side of island; High flows – upper pool deposit, as most water directed to other side of island.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; area eroded in part by overflow from Espejo Creek.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1996 and presence of 1983 deposits indicate deposition from flows above 45,000 cfs.

Average Vulnerability of Terraces: A = 24, B = 21
Vulnerability of Top Terrace: A = 43, B = 40
Anomalies: overflow from Espejo Creek; pre-dam arroyo cutting

SITE: COMANCHE CREEK (Catchment E; C and D eliminated)

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope; narrow width of sand terraces; low number of terrace levels.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow dominant processes on ap level; infiltration and piping aids in nickpoint development.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda terrace is thickly vegetated and undissected.
RIVER PROCESSES: PPC flows - separation bar below the mouth of Espejo Creek; High flows - separation and reattachment bar at flows less than about 60,000 cfs as evidenced by 1996 deposit; lack of 1983 deposit indicates that area becomes a channel margin setting at flows above 45,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; no 1983 deposit here.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 sand indicate depositional environment at around 45,000 cfs; lack of 1983 flood sand and steep embankment indicate erosional setting at flows above about 60,000 cfs.

Average Vulnerability of Terraces: E = 0
Vulnerability of Top Terrace: E = 0
Anomalies: thick vegetation on pda terrace

SITE: COMANCHE CREEK (Catchment F)

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area; low number of terraces.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation is dominant process; infiltration and piping through pervasive burrows in ap terrace has induced extensive nickpoint migration. Steep escarpment along the river indicates oversteepening by pre-dam flows, which likely induced nickpoint migration.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Well-developed and vegetated pda here; keeps base level of drainage at pda level.
RIVER PROCESSES: PPC flows - channel margin bar; High flows - channel margin setting that gets eroded at flows above 45,000 cfs; probably forms upper pool deposit at very high flows (>125,000 cfs).
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; no evidence of 1983 deposit; pre-dam bank retreat.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1996 and 1983 deposits suggests that this area becomes eroded at flow above PPC and below 125,000 cfs.

Average Vulnerability of Terraces: F = 70
Vulnerability of Top Terrace: F = 70
Anomalies: bank retreat may have generated nickpoint migration; arroyo cutting in pre-dam time; high drainage density in upper catchment

SITE: COMANCHE CREEK (Catchment H: G and I eliminated)

GEOMORPHIC SETTING: Alluvial fan
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation most prominent process; some ponding and overflow occurs on ap terrace.

CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda is well developed but is incised by this catchment
RIVER PROCESSES: PPC flows - channel margin bar; High flows - upper pool deposit that forms a small recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 and 1983 flood sands indicates depositional zone at flows above 45,000 cfs.

Average Vulnerability of Terraces: H = 67
Average Vulnerability of Terraces: H = 67
Anomalies: river based; high drainage density in upper catchment

SITE: COMANCHE CREEK (Catchment J)

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: Overflow from Comanche Creek.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: No evidence of process could be found here; old arroyo with mature vegetation and cryptogam development; incised in pre-dam time.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda terrace is incised by this channel.
RIVER PROCESSES: PPC flows - separation bar; High flows - separation bar without reattachment deposit.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; eroded by side-canyon overflow; no 1983 sand present.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1996 and 1983 sand indicates poor potential for deposition; however, gravel deposits at 1983 level would prevent scarp retreat from flood flows.

Average Vulnerability of Terraces: J = 19
Vulnerability of Top Terrace: J = 33
Anomalies: pre-dam arroyo cutting and subsequent revegetation keep drainage very stable even though it is river based

SITE: COMANCHE CREEK (Catchment K)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Bedrock slope directly adjacent to ap terrace; human trailing.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation (comprised of Dox shale).
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Pda is extensive and relatively unincised.
RIVER PROCESSES: PPC flows - reattachment bar; High flows - reattachment bar in large recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOW: Presence of 1996 and 1983 sand indicates depositional zone at flows above PPC flows.

Average Vulnerability of Terraces: K = 43
Vulnerability of Top Terrace: K = 79
Anomalies: sand portion of catchment fed by runoff from bedrock

SITE: TANNER CANYON (Catchments A, B)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Overflow from adjacent large catchment for A; steep bedrock slope; high percent bare ground.
BASE LEVEL OF CHANNEL: Pda terrace for A; lmt terrace for B.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation consisting of Dox fine gravel is dominant process. Ponding and overflow from narrow ap/sa terrace to lower terraces. Thick vegetation on lmt prevents B from integrating with the river.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Only small, discontinuous segments are present.
RIVER PROCESSES: PPC flows - point bar deposit; High flows - point bar deposit up to about 60,000 cfs; above 60,000 cfs. cutoff channel from the river flows along the base of steep escarpment on the left side of the Tanner bar creating a channel margin setting.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; arroyos formed in pre-dam time; bank retreat due to pre-dam floods that formed channel to left side of the Tanner bar.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 sand along Tanner bar indicates some deposition; however, flows above 60,000 cfs could erode parts of the pda escarpment; lack of 1996 flood sand indicates little benefit from flows below 45,000 cfs.

Average Vulnerability of Terraces: A = 16, B = 19
Vulnerability of Top Terrace: A = 18, B = 36
Anomalies: very high ap/sa escarpment; arroyo development started in pre-dam time; 1983 flood carved channel on left side of Tanner bar

SITE: BASALT CANYON (Catchment A)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Small number of terraces; high percent bare ground.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration with small amount of piping; eolian processes very active, causing swale of channel to be continuously infilled with sand.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): If it exists, it is covered with eolian sand
RIVER PROCESSES: PPC flows - reattachment bar; High flows - separation and reattachment bar in a large recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist except pda terrace (probably covered with eolian sand).
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 and 1983 flood sands indicates a depositional zone at flows above PPC.

Average Vulnerability of Terraces: A = 24
Vulnerability of Top Terrace: A = 30
Anomalies: constant eolian infilling

SITE: BASALT CANYON (Catchment B)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Scarp retreat from the river; high percent bare ground; low number of terraces; very steep sand slope.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow off of ap/sa terrace and onto lower terraces; infiltration and piping result of shallow sand depth overlying gravel.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): No pda sand, only gravel.
RIVER PROCESSES: PPC – channel margin setting; High flows – channel margin bar; probably erosional at flows up to about 60,000 cfs as evidenced by lack of 1996 sand; marginal deposition at flows from 60,000 cfs to 100,000 cfs, as only thin 1983 deposit exists.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 2.0; bank retreat caused by river channel geometry; no pda sand, only gravel.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: The lack of 1996 flood sand indicates little benefit from flows up to 45,000 cfs; only small amount of 1983 sand indicates marginal deposition from flows 60,000-100,000 cfs.

Average Vulnerability of Terraces: B = 19
Vulnerability of Top Terrace: B = 27
Anomalies: very steep headcut in steep ap riser; shallow sand depth

SITE: BASALT CANYON (Catchments C, C')

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Scarp retreat from the river; steep sand slope.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow off of ap/sa terrace and onto lower terraces; infiltration and piping result of shallow sand depth overlying gravel.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): No sand present, only gravel.
RIVER PROCESSES: PPC – channel margin setting; High flows – channel margin bar; probably erosional at flows up to about 60,000 cfs as evidenced by lack of 1996 sand; marginal deposition at flows from 60,000 cfs to 100,000 cfs, as only thin 1983 deposit exists.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; bank retreat caused by river channel geometry; no pda sand, only gravel.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: The lack of 1996 flood sand indicates little benefit from flows up to 45,000; only small amount of 1983 sand indicates little deposition from flows 60,000-100,000 cfs.

Average Vulnerability of Terraces: C = 10, C' = 0
Vulnerability of Top Terrace: C = 13, C' = 0
Anomalies: steep ap riser; shallow sand depth

SITE: BASALT CANYON (Catchment D)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: High percent bare ground.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping result of abundant gravel mixed with sand on ap/sa terrace.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Present here, but has been incised by Catchment D.
RIVER PROCESSES: PPC flows – upper pool deposit; High flows – separation bar with depositional zone at flows above PPC; lack of 1983 sand indicates erosional area above about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no 1983 sand.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 sand indicates deposition above PPC flows; lack of 1983 sand indicates poor area of deposition at flows above about 60,000 cfs.

Average Vulnerability of Terraces: D = 10
Vulnerability of Top Terrace: D = 19

SITE: LOWER TANNER (Catchments A, B)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area for A.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow prevalent, mostly in A, which caused eolian dunes to be breached and eroded. B formed as a small and deep distributary channel of A when it overflowed from ponding.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive; relatively unincised.
RIVER PROCESSES: PPC flows – channel margin bar: High flows – channel margin bar; presence of 1996 and a little 1983 sand suggests a narrow recirculation zone at flows above PPC.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.25; all base-level properties exist, except no 1983 flood sand present, only gravel.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Narrow depositional zone because of channel margin setting; good potential for deposition above PPC flows.

Average Vulnerability of Terraces: A = 20, B = 19
Vulnerability of Top Terrace: A = 34, B = 36
Anomalies: lots of eolian infilling and gentle slope

SITE: LOWER TANNER (Catchment C)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area; scarp retreat; high percent bare ground.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation of Dox fine gravel.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Very narrow and discontinuous segment.
RIVER PROCESSES: PPC flows - channel margin bar; High flows - small reattachment bar that forms in small recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; scarp retreat from river flood flows.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1996 and small deposit of 1983 sand indicates only small amount of deposition at flows above 45,000 cfs.

Average Vulnerability of Terraces: C = 11
Vulnerability of Top Terrace: C = 28
Anomalies: active dunes

SITE: LOWER TANNER (Catchments D, E)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Overflow channels from side canyon.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation of Dox fine gravel.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive; undissected.
RIVER PROCESSES: PPC flows - channel margin setting; High flows - channel margin bar at flows above PPC; no recirculation zone at flows above 45,000 cfs, as evidenced by lack of 1983 sand.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; overflow channels from side canyon; no 1983 sand, only gravel.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 sand and lack of 1983 sand indicate a depositional zone above PPC flows and below about 60,000 cfs.

Average Vulnerability of Terraces: D = 20, E = 22
Vulnerability of Top Terrace: D = 37, E = 31
Anomalies: overflow channels from side canyon

SITE: LOWER TANNER (Catchment F)

GEOMORPHIC SETTING: Alluvial fan
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area.
BASE LEVEL OF CHANNEL: Lmt terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation of Dox fine gravel; ponding and overflow evident in interdune areas.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive.
RIVER PROCESSES: Reattachment bar for D and E, channel margin bar for A-C and F.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no 1983 sand, only gravel.

POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 sand and lack of 1983 sand indicate a depositional zone above PPC flows and below about 60,000 cfs.

Average Vulnerability of Terraces: F = 46
Anomalies: much eolian influence; channel is aggradational

SITE: UPPER UNKAR (Catchments A, B, C)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Narrow terrace width; steep sand slope; high percent bare ground.
BASE LEVEL OF CHANNEL: A-G on pda terrace. H on 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation of Dox gravel; excavation done on D in 1984, no new headcut migration since last year.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide at A-E, but decreasing to zero in the downstream direction at F-H.
RIVER PROCESSES: PPC flows – channel margin setting; High flows – narrow recirculation zone along a channel margin bar at high flows (>60k).
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 and 1983 sand deposits indicates depositional setting at flows above PPC.

Average Vulnerability of Terraces: A = 28, B = 0, C = 0
Vulnerability of Top Terrace: A = 43, B = 1, C = 0

SITE: UPPER UNKAR (Catchment D)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Narrow terrace width; steep sand slope; high percent bare ground; excavation of site.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation of Dox gravel; excavation in 1984 could have exacerbated channel incision or headcut development.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive.
RIVER PROCESSES: PPC flows – channel margin setting; High flows – narrow recirculation zone along a channel margin bar at high flows (>60k).
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 and 1983 sand deposits indicates depositional setting at flows above PPC.

Average Vulnerability of Terraces: D = 25
Vulnerability of Top Terrace: D = 46
Anomalies: excavated site

SITE: UPPER UNKAR (Catchments E-H)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Narrow terrace width; steep sand slope; high percent bare ground; steep bedrock slope.
BASE LEVEL OF CHANNEL: Pda terrace; H based on 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation of Dox gravel.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Narrow but undissected.
RIVER PROCESSES: PPC flows - channel margin setting; High flows - narrow recirculation zone along a channel margin bar at high flows (>60k).
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 and 1983 sand deposits indicates depositional setting at flows above PPC.

Average Vulnerability of Terraces: E = 22, F = 22, G = 23, H = 24
Vulnerability of Top Terrace: E = 38, F = 34, G = 37, H = 37
Anomalies: some eolian influence

SITE: OLD UNKAR CAMP (Catchment A)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope; narrow width of sandy terraces; scarp retreat from 1984-1986 flows.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Used to be extensive wide terrace in the 1960s–1970s, making for a good camp (Belknap photo); high sustained flows in 1980s probably caused erosion of most of the pda.
RIVER PROCESSES: PPC flows - channel margin setting; High flows - small eddy in a re-entrant along a channel margin bar setting.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no 1983 sand.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 sand and former presence of 1983 sand indicate a depositional zone at flows above PPC.

Average Vulnerability of Terraces: A = 28
Vulnerability of Top Terrace: A = 37
Anomalies: interbedding of fluvial and eolian deposits, particularly in the pda; evidence that eolian deposition was an important process at this site in the pre-dam period; lack of new deposition has disrupted this equilibrium

SITE: LOWER UNKAR (Catchments A, B)

GEOMORPHIC SETTING: Alluvial fan
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area; high percent bare ground; steep riser of sa terrace.
BASE LEVEL OF CHANNEL: 1983 terrace level.

PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation of Dox fine gravel across the pda and 1983 sand terraces; eolian sand (from 1983 and pda flood sands) has blown up onto ap/sa terrace riser and into mouths of arroyos.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive terrace; alluvial fans overlie and are interbedded with pda sand.
RIVER PROCESSES: PPC flows - channel margin bar; High flows - channel margin at flows up to about 60,000 cfs; upper pool deposit at flows above about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; deep arroyos present in pre-dam time; presence of 1983 and pda sand has helped to slow channel extension toward the river; much 1983 sand has been blown up into arroyo mouths, was partly removed by 1984-1986 flows.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 flood sands indicates a depositional zone at flows above PPC; only remnants of 1983 sand remain across gravel bar, since it was partly removed by 1984-1986 flows.

Average Vulnerability of Terraces: A = 39, B = 45
Vulnerability of Top Terrace: A = 43, B = 46
Anomalies: very deep arroyos cut into extensive ap/sa terrace; risers and arroyo mouths blanketed with eolian sand (from 1983 and pda source); interbedded alluvial fans and river sand support base-level hypothesis; aggradation at arroyo mouths help slow channel from reaching river

SITE: LOWER UNKAR (Catchment C)

GEOMORPHIC SETTING: Alluvial fan
PRINCIPLE FACTORS DRIVING EROSION: High percent bare ground; steep riser of sa terrace.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation of Dox fine gravel across the pda and 1983 sand terraces; 1983 sand has been blown up into arroyo mouth; pda and mt sand have blown up onto ap/sa terrace riser.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive terrace; alluvial fans overlie and are interbedded with pda sand.
RIVER PROCESSES: PPC flows - channel margin bar; High flows - channel margin at flows up to about 60,000 cfs; upper pool deposit at flows above about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; deep arroyos present in pre-dam time; presence of 1983 and pda sand has helped to slow channel extension toward the river; much 1983 sand has been blown up into arroyo mouths, was partly removed by 1984-1986 flows.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 flood sands indicates a depositional zone at flows above PPC; only remnants of 1983 sand remain across gravel bar, since it was partly removed by 1984-1986 flows.

Average Vulnerability of Terraces: C = 29
Vulnerability of Top Terrace: C = 36
Anomalies: very deep arroyos cut into extensive ap/sa terrace; risers and arroyo mouths blanketed with eolian sand (from 1983 and pda source); interbedded alluvial fans and river sand support base-level hypothesis; aggradation at arroyo mouths helps slow channel from reaching river

SITE: 122 MILE CANYON (Catchment A)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: High percent bare ground.
BASE LEVEL OF CHANNEL: Mt level (gravel).
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping dominant on ap terrace.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present here.
RIVER PROCESSES: PPC flows - separation bar in large eddy; High flows - separation bar in large recirculation zone; depositional at flows above PPC.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no pda level.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates a large depositional area.

Average Vulnerability of Terraces: A = 3
Vulnerability of Top Terrace: A = 9
Anomalies: 1996 and 1983 sand locally reworked by wind around catchment, but not directly in catchment; diversion bar built at talus/sand contact

SITE: 122 MILE CANYON (Catchment B)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Small number of terraces; steep sand slope; human trailing; bedrock directly under sand.
BASE LEVEL OF CHANNEL: Pda terrace in 122 Mile drainage.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping; can see points where water enters a small pipe and emerges just downslope; scarp retreat from side canyon erosion.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Small segments still present in side canyon.
RIVER PROCESSES: PPC flows - separation bar in large eddy; High flows - separation bar in large recirculation zone; depositional at flows above PPC; sediment will be deposited into side canyon at flows above about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; base level of B actively eroded by side canyon; no 1983 deposit (although presumably the deposit once existed in the side canyon).
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand near the river indicates a large depositional area; flows above about 60,000 cfs should deposit sediment at the base of B.

Average Vulnerability of Terraces: B = 21
Vulnerability of Top Terrace: B = 30
Anomalies: side canyon based stream; bedrock based

SITE: 122 MILE CANYON (Catchments C, D)

PRINCIPLE FACTORS DRIVING EROSION: High percent bare ground; narrow width of sandy terraces; steep sand slope; human trailing.
BASE LEVEL OF CHANNEL: 1983 terrace.

PROCESS OF CHANNEL INTEGRATION: Infiltration and piping through the narrow ap terrace have resulted in headcut migration, headcut in C has migrated 3.1 m since April 1998; 1983 sand being blown upslope into gully mouths, helping to prevent channels from reaching river.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present here (although it is probably covered over by 1983 sand that has blown upslope).
RIVER PROCESSES: PPC flows - reattachment in large eddy; High flows - reattachment bar in large recirculation zone; large depositional zone at flows above PPC, where high elevation sand bar forms.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no pda level.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand near the river indicates a large depositional area; high elevation sand deposited at flows above PPC.

Average Vulnerability of Terraces: C = 12, D = 15
Vulnerability of Top Terrace: C = 17, D = 21
Anomalies: large amount of 1983 and 1996 sand is locally reworked upslope by eolian processes

SITE: OWL EYES (Catchments A, A')

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Small number of terraces.
BASE LEVEL OF CHANNEL: Pda level in side canyon.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow prevalent in interdune areas; infiltration and piping likely occurs within the dunes - catchment is composed almost exclusively of old dunes that provide high infiltration rates from rainfall.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present in side canyon, but present upstream and downstream on debris fan.
RIVER PROCESSES: PPC flows - channel margin setting; High flows - upper pool; tributary mouth receives slackwater and slow-moving eddy deposits at flows above 45,000 cfs; sediment backs up into side canyon at flows above about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; mouth of drainage actively eroded by side canyon; no 1983 or pda sand present (although it probably once existed before side-canyon erosion).
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1983 and 1996 sand up in the side canyon indicates poor potential for restoration of A and A'.

Average Vulnerability of Terraces: A = 17, A' = 23
Vulnerability of Top Terrace: A = 29, A' = 36
Anomalies: old, well vegetated dunes that provide stable environment

SITE: OWL EYES (Catchments B, B')

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Low number of terraces; high percent bare ground.
BASE LEVEL OF CHANNEL: Pda terrace covered with active eolian sand.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation composed of sand; extensive eolian dunes at 1983 and pda levels help prevent channel from reaching river or side canyon.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly extensive; reworked by wind and partially blown upslope.

RIVER PROCESSES: PPC flows – channel margin; High flows – separation bar that becomes depositional area at flows above PPC.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no 1983 sand, early gravel (1983 sand once existed but has since been reworked into dune).
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996s and indicates deposition at flows above PPC; 1983 sand once existed, but has been reworked by wind; probably forms large separation bar at flows above about 60,000 cfs.

Average Vulnerability of Terraces: B = 0, B' = 1
Vulnerability of Top Terrace: B = 0, B' = 2
Anomalies: 1983 sand has been scoured and redeposited by wind onto pda level

SITE: FISHTAIL CANYON (Catchment A)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Human trailing; steep sand slope; narrow terrace width, high percent bare ground.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation is the dominant process; some evidence of infiltration and piping at mt level; upslope human trailing has caused channel incision at mt and ap levels.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly extensive and covered with eolian sand; relatively undissected, with alluvial fans forming across terrace.
RIVER PROCESSES: PPC flows – upper pool deposit; High flows – upper pool deposit with recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates upper pool depositional zone for flows above PPC.

Average Vulnerability of Terraces: A = 10
Vulnerability of Top Terrace: A = 27
Anomalies: 1983 sand has been blown partially upslope; severe human trailing will lead to severe gully erosion

SITE: 140 MILE CANYON (Catchment A)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope; high percent bare ground.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation is dominant process.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Thin terrace width, has been incised by A.
RIVER PROCESSES: PPC flows – upper pool deposit; High flows – upper pool deposit with recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates recirculation zone for deposition at flows above PPC.

Average Vulnerability of Terraces: A = 19
Vulnerability of Top Terrace: A = 29
Anomalies: evidence of eolian infilling from 1983 sand

SITE: SADDLEHORSE CANYON (Catchment A)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope; high percent bare ground; narrow width of sandy terraces.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation is dominant process; some infiltration and piping evident in ap and mt terraces; recent stream capture with other channels.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Relatively wide but not extensive; incised by A.
RIVER PROCESSES: PPC flows - upper pool eddy; High flows - upper pool deposit that forms small depositional recirculation area.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates a depositional recirculation zone at flows above PPC.

Average Vulnerability of Terraces: A = 32
Vulnerability of Top Terrace: A = 45
Anomalies: stream capture with other channels

SITE: SADDLEHORSE CANYON (Catchment B)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope; high percent bare ground.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow primary processes in interdune areas.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Thin deposit that has not yet been incised.
RIVER PROCESSES: PPC flows - separation eddy; High flows - separation deposit at flows above about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and lack of 1996 deposits indicate depositional zone at flows above about 60,000 cfs.

Average Vulnerability of Terraces: B = 11
Vulnerability of Top Terrace: B = 17
Anomalies: thick cryptogamic soil seems to keep site stable

SITE: 183 MILE (Catchment A)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope; narrow width of sandy terraces.
BASE LEVEL OF CHANNEL: Mt terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping, alluvial fan progradation are equally influential.

CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Narrow terrace with little sand, only gravel; unincised because of gravel.
RIVER PROCESSES: PPC flows – channel margin bar; High flows – (undetermined)
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; no 1983 or pda sand, only gravel.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1983 and presence of 1996 sand indicate small depositional zone at flows above PPC and below about 60,000 cfs (further investigation of air photos needed).

Average Vulnerability of Terraces: A = 0
Vulnerability of Top Terrace: A = 0
Anomalies: thickly vegetated; scarp retreat from river is probable

SITE: 186 MILE (Catchment A)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope; high percent bare ground.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation of sand from large dune complex above.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive; alluvial fan forming on this terrace.
RIVER PROCESSES: PPC flows – channel margin bar; High flows – upper pool deposit.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and lack of 1996 sand indicate depositional recirculation zone above 45,000 cfs.

Average Vulnerability of Terraces: A = 7
Vulnerability of Top Terrace: A = 21
Anomalies: eolian infilling process dominates the site; mesquite bosque stabilizes the dune complex

SITE: 190 MILE CANYON (Catchment A)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Moderately large catchment area.
BASE LEVEL OF CHANNEL: Pda level.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping, alluvial fan progradation are main processes; channel presently debouches at gravel bar; sand aggradation in channel indicates that base level is maintained at a high elevation due to high elevation gravel bar.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): No sand present; only extensive gravel bar with driftwood lines;.depositional until flows exceed about 100,000 cfs, then upper pool recirculation zone.
RIVER PROCESSES: PPC flows – upper pool eddy; High flows – upper pool eddy that is non-depositional.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; no pda or 1983 sand, only gravel
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1983 and 1996 sand indicates an upper pool eddy that is mostly non-depositional; recirculation zone forms at flows above 100,000 cfs.

Average Vulnerability of Terraces: A = 44
Vulnerability of Top Terrace: A = 53

Anomalies: sand aggradation in channel; mesquite bosque at lower terrace level; high gravel bar at mouth

SITE: 194 MILE CANYON (Catchment A)

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area; steep bedrock slope.
BASE LEVEL OF CHANNEL: Umt terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping dominant processes; evidence of piping through animal burrows in tread.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive; unincised.
RIVER PROCESSES: PPC flows – channel margin deposit; High flows – upper pool deposit; depositional recirculation zone at flows above PPC.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates deposition at flows above PPC.

Average Vulnerability of Terraces: A = 37
Vulnerability of Top Terrace: A = 47
Anomalies: extremely wide sa/ap terrace; channel more like a swale with vegetation; barrier dune formed below mouth of catchment

SITE: 196 MILE (Catchment A)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Steep talus slope; human trailing.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation is dominant process; infiltration and piping evident on mt terrace; channel now follows surveyor's trail at pda level.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Very wide and continuous; alluvial fans form across terrace.
RIVER PROCESSES: PPC flows – channel margin deposit; High flows – channel margin up to flows of 45,000 cfs; reattachment bar at flows above about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates depositional zones at flows above PPC; large recirculation zone above 60,000 cfs provides large depositional area.

Average Vulnerability of Terraces: A = 27
Vulnerability of Top Terrace: A = 67
Anomalies: very wide 1983 deposit prevents channel from reaching river; very steep sand slope from ap through pda level

SITE: 201 MILE (Catchments A-D)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Very steep ap riser.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping predominant processes; many burrows and pipes noted throughout all pre-dam terraces; big storm in winter of 1998-99 caused B, C, D to be integrated into one channel system; alluvial fan progradation evident on umt terrace.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Narrow but extensive terrace; incised by channels.
RIVER PROCESSES: PPC flows – upper pool eddy; High flows – upper pool deposit with recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates a depositional area above PPC flow

Average Vulnerability of Terraces: A = 31, B = 20, C = 20, D = 20
Vulnerability of Top Terrace: A = 60, B = 47, C = 47, D = 47
Anomalies: steep ap riser; many burrows for piping and surface collapse

SITE: 201 MILE (Catchment E)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope.
BASE LEVEL OF CHANNEL: Side canyon.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping predominant; alluvial fan formed on umt terrace; data recovery done by NPS in winter of 1999.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present.
RIVER PROCESSES: PPC flows – upper pool eddy; High flows – upper pool deposit with recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; actively eroded by side canyon; no pda or 1983 deposits.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1983 and 1996 sand in side canyon indicates poor restorative potential.

Average Vulnerability of Terraces: E = 13
Vulnerability of Top Terrace: E = 21
Anomalies: drains to side canyon

SITE: 202 MILE (Catchment A)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope; high percent bare ground; human trailing.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Little evidence of process; some infiltration and piping in mt and ap terraces; winter storm of 1998 caused renewed incision and nickpoint migration; mouth of channel debouches onto gravel bar at river.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present.

RIVER PROCESSES: PPC flows - upper pool eddy; High flows - upper pool deposit; area forms recirculation zone at flows above PPC.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no pda sand.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates a depositional recirculation zone at flows above PPC.

Average Vulnerability of Terraces: A = 37
Vulnerability of Top Terrace: A = 43
Anomalies: channel debouches onto gravel bar at river; human trailing; eolian reworking of 1983 deposit

SITE: 202 MILE (Catchment B)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope; high percent bare ground; human trailing.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Human trailing straight upslope above the camp on steep dune face; ponding and overflow also contributes to incision; winter storm of 1999 renewed channel incision and nickpoint migration.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present.
RIVER PROCESSES: PPC flows - separation bar; High flows - separation bar with large recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no pda sand.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates a depositional setting for flows above PPC.

Average Vulnerability of Terraces: B = 4
Vulnerability of Top Terrace: B = 8
Anomalies: severe human trailing; some eolian influx

SITE: INDIAN CANYON (Catchment A)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: No predominant Principle Factors.
BASE LEVEL OF CHANNEL: Lmt level (bedrock).
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping predominant processes; several large roasters at top of terrace sequence absorb runoff from talus above.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present; level is bedrock.
RIVER PROCESSES: PPC flows - channel margin area at bedrock; High flows - channel margin deposit; no depositional area at flows above PPC and below 300,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; no pda or 1983 deposits; no eolian reworking.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1983 and 1996 sand indicates no deposition with flows above PPC.

Average Vulnerability of Terraces: A = 10
Vulnerability of Top Terrace: A = 16
Anomalies: bedrock based; only floods exceeding 225 K will help base level here

SITE: INDIAN CANYON (Catchment B)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Human trailing.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Human trailing; some infiltration and piping at ap and umt levels; large roasters at top of terrace sequence absorb some runoff from talus above.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present; level is bedrock.
RIVER PROCESSES: PPC flows - channel margin area at bedrock; High flows - channel margin deposit; no depositional area at flows above PPC and below 300,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 3.0; no pda or 1983 deposits; no eolian reworking.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1983 and 1996 sand indicates no deposition with flows above PPC.

Average Vulnerability of Terraces: B = 16
Vulnerability of Top Terrace: B = 24
Anomalies: bedrock based; severe human trailing

SITE: ARROYO GRANDE (Catchment A)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Extremely large catchment.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Retreating scarp along the river (from pre-dam flows); infiltration and piping: subsurface pipes and animal burrows ubiquitous across ap/sa and lmt terraces: alluvial fan progradation apparent at talus and ap/sa contact.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present.
RIVER PROCESSES: PPC flows - channel margin deposit; High flows - channel margin at flows between PPC and 45,000 cfs; upper pool eddy at flows above about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 2.0; pre-dam arroyo cutting; pre-dam scarp retreat from river flows; no pda sand.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates depositional zones at flows above PPC.

Average Vulnerability of Terraces: A = 59
Vulnerability of Top Terrace: A = 59
Anomalies: pre-dam arroyo cutting; arroyo has been rejuvenated in post-dam time; lots of roasters (could influence infiltration and piping)

SITE: ARROYO GRANDE (Catchment A')

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: No predominant Principle Factors.
BASE LEVEL OF CHANNEL: Mt terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping through ubiquitous burrows in wide ap terrace; alluvial fan progradation apparent at sa/ap and talus slope contact.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Wide and fairly extensive terrace.
RIVER PROCESSES: PPC flows - channel margin deposit: High flows - upper pool deposit with recirculation zone at flows above PPC.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates depositional recirculation zone at flows above PPC.

Average Vulnerability of Terraces: A' = 5
Vulnerability of Top Terrace: A' = 16
Anomalies: possible pre-dam arroyo cutting; many roasters (might somehow influence infiltration and piping)

SITE: ARROYO GRANDE (Catchment B)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: Steep bedrock slope.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping through ubiquitous burrows in wide ap terrace; alluvial fan progradation apparent at sa/ap and talus slope contact.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly extensive terrace: dissected by this channel.
RIVER PROCESSES: PPC flows - channel margin deposit: High flows - upper pool deposit with recirculation zone at flows above PPC.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; possible pre-dam arroyo cutting.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and lack of 1996 sand indicate depositional recirculation zone at flows above about 60,000 cfs.

Average Vulnerability of Terraces: B = 11
Vulnerability of Top Terrace: B = 27
Anomalies: possible pre-dam arroyo cutting; steep mt riser; many roasters (might somehow influence infiltration and piping)

SITE: ARROYO GRANDE (Catchments C-E)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope at ap level; small number of terrace levels.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation: fans forming on 1983 level.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present here.
RIVER PROCESSES: PPC flows - channel margin deposit: High flows - upper pool deposit with recirculation zone at flows above PPC.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0: no pda sand.

POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 sand and lack of 1996 sand indicate depositional recirculation zone at flows above about 60,000 cfs.

Average Vulnerability of Terraces: C = 23, D = 17, E = 4
Vulnerability of Top Terrace: C = 33, D = 26, E = 7
Anomalies: very steep ap riser

SITE: GRANITE PARK (Catchment A)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow predominant process of initiating headcuts; infiltration and piping evident on pda terrace; alluvial fan progradation also noted on some of the terraces.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive; incised by this channel.
RIVER PROCESSES: PPC flows - channel margin bar; High flows - upper pool with recirculation zone at flows above PPC.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 flood sands indicates a depositional recirculation zone at flows above PPC.

Average Vulnerability of Terraces: A = 36.2
Vulnerability of Top Terrace: A = 52
Anomalies: old dune at ap level

SITE: GRANITE PARK (Catchments B, B'; C eliminated)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: No predominant Principle Factors.
BASE LEVEL OF CHANNEL: Pda terrace.
PROCESS OF CHANNEL INTEGRATION: Ponding and overflow predominant process of initiating headcuts; infiltration and piping evident on pda terrace.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Fairly wide and extensive.
RIVER PROCESSES: PPC flows - channel margin bar; High flows - channel margin with small recirculation area at flows above PPC and below about 60,000 cfs; above about 60,000 cfs no recirculation zone exists.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no 1983 sand, only gravel.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1983 and presence of 1996 flood sands indicate a depositional recirculation zone at flows above PPC and below about 60,000 cfs.

Average Vulnerability of Terraces: B = 5, B' = 5
Vulnerability of Top Terrace: B = 21, B' = 15
Anomalies: checkdams have been overtopped, causing channel widening and nickpoint migration
SITE: GRANITE PARK (Catchments D, D')

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area for D.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Alluvial progradation is dominant process; alluvial fans present on each terrace; some infiltration and piping evident at terrace risers.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Wide in this area; dissected by these drainages.
RIVER PROCESSES: PPC flows - channel margin bar; High flows - channel margin with small depositional area at flows above PPC and below about 60,000 cfs; channel margin bar becomes erosional at flows above 60,000 cfs
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no 1983 sand.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1983 sand and presence of 1996 flood sands indicate a depositional area at flows up to about 60,000 cfs.

Average Vulnerability of Terraces: D = 23, D' = 0
Vulnerability of Top Terrace: D = 41, D' = 0
Anomalies: checkdams placed in D

SITE: GRANITE PARK (Catchments E, F)

GEOMORPHIC SETTING: Tributary plain
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area; narrow width of sandy terraces.
BASE LEVEL OF CHANNEL: Side canyon.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping predominant process; broad terraces are effective at diffusing large runoff events that flow onto them.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): No sand present, only gravel.
RIVER PROCESSES: PPC flows - does not affect tributary, upper pool eddy at river; High flows - small amount of sand will back up into mouth, upper pool deposit at river.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 2.0; area actively eroded by side canyon; no pda or 1983 sand deposits; no eolian infilling of catchment.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1983 and 1996 deposits indicates little sand deposition in mouth; only small amount of sand will back up into mouth until tributary obliterates it; umt slack-water deposits located where this catchment debouches.

Average Vulnerability of Terraces: E = 86, F = 46
Vulnerability of Top Terrace: E = 86, F = 57
Anomalies: eo deposit diverts path of E and F into tributary

SITE: GRANITE PARK (Catchment G)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: No predominant Principle Factors.
BASE LEVEL OF CHANNEL: 1983 terrace.
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping dominant process here; particularly evident in inactive eolian dune complex.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Not present.

RIVER PROCESSES: PPC flows - channel margin bar; High flows - separation deposit with recirculation zone at flows above about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; no pda sand.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 sand and lack of 1996 sand indicate a depositional zone at flows above about 60,000 cfs.

Average Vulnerability of Terraces: G = 0
Vulnerability of Top Terrace: G = 0
Anomalies: deeply incised into dune but stabilized by abundant vegetation; restored by active eolian in upper dune complex

SITE: GRANITE PARK (Catchment H)

GEOMORPHIC SETTING: Debris lobe
PRINCIPLE FACTORS DRIVING EROSION: Large catchment area.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping dominant process here; particularly evident in inactive eolian dune complex.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Narrow terrace with large patches of 1983 eolian sand blown up onto it.
RIVER PROCESSES: PPC flows - channel margin deposit; High flows - separation deposit with recirculation area at flows above PPC and below about 60,000 cfs.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; all base-level properties exist, except no 1983 sand, only gravel.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1996 sand and lack of 1983 sand indicate a depositional area at flows above PPC and below about 60,000 cfs.

Average Vulnerability of Terraces: H = 44
Vulnerability of Top Terrace: H = 50
Anomalies: deeply incised channel with many active nickpoints migrating upstream, probably in response to erosion of buttressing sand bars along the river; inactive eolian dune complex, which forms one side of channel in dune complex, is highly erodible and easily degraded by runoff from the talus slope above

SITE: 209.3 MILE (Catchments A-C)

GEOMORPHIC SETTING: Talus slope
PRINCIPLE FACTORS DRIVING EROSION: No predominant Principle Factors.
BASE LEVEL OF CHANNEL: River for A and B; pda terrace for C.
PROCESS OF CHANNEL INTEGRATION: Alluvial fan progradation is predominant process; most evident on pda terrace level; deep incision of arroyos has occurred by infiltration and piping at ap and mt levels.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Very thin veneer of sand on a river gravel bar base; small alluvial fans across pda level.
RIVER PROCESSES: PPC flows - point bar; High flows - point bar with no recirculation zone.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 4.0; no 1983 sand and little to no pda sand.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Lack of 1983 and 1996 sand indicates a point bar setting with no depositional zone; large gravel bar would prevent high-flow erosion.

Average Vulnerability of Terraces: A = 44, B = 64, C = 9

Vulnerability of Top Terrace: A = 69, B = 67, C = 19
***Anomalies:** A and B have become river based during the 1998 monsoon, further degraded by winter storm in 1998-99*

SITE: FALL CANYON (Catchment A)

PRINCIPLE FACTORS DRIVING EROSION: Steep sand slope and narrow width of ap/sa terrace; human trail directly upslope.
BASE LEVEL OF CHANNEL: River
PROCESS OF CHANNEL INTEGRATION: Infiltration and piping dominant process; human trailing rejuvenated channel erosion; increased erosion after 1998 monsoon and again in winter of 1998-99.
CONDITION OF PRE-DAM ALLUVIUM (PDA TERRACE): Narrow; incised by many channels that drain off slope.
RIVER PROCESSES: PPC flows - upper pool eddy; High flows - upper pool eddy with large recirculation zone at flows above PPC.
STRENGTH OF BASE-LEVEL HYPOTHESIS: Rating = 5.0; all base-level properties exist.
POTENTIAL BENEFIT OF A RESTORATIVE FLOOD FLOW: Presence of 1983 and 1996 sand indicates a large depositional area at flows above PPC.

Average Vulnerability of Terraces: A = 14
Vulnerability of Top Terrace: A = 25
***Anomalies:** about 150 square meters of active eolian sand on the ap/sa provides infilling of gullies; eolian reworking adjacent to channel; cryptogamic soil very well developed on 1983 sand terrace; eddy at the base of catchment was the locus for deposition of large amounts of sand in 1984 air photo*

APPENDIX C

SUMMARY OF CATCHMENT DATA USED IN MODEL

Summary of Catchment Data Used in Model

Order	River Mile	River Side	Catch-ment	Location	Geomorphic Setting	catchment area m2	gul dep ratio	runoff Q m3	dischrgeQp m3/sec	1996 sand present?	1983 sand present?	pda sand present?	dune field % area
				Grand Canyon									
1	1.1	R	A	Paria	talus slope	2057	0.54	18	0.12	no	yes	yes	9%
2	1.1	R	B	Paria	talus slope	695	0.61	6	0.10	no	yes	yes	2%
3	2.0	L	A	Axe Handle Cove	talus slope	85638	1.00	1704	4.15	yes	yes	no	0%
4	2.0	L	B	Axe Handle Cove	talus slope	1748	0.55	15	0.35	yes	yes	no	0%
5	2.0	L	C	Axe Handle Cove	talus slope	146324	0.03	2425	18.58	no	yes	yes	0%
6	10.0	R	A	Ten Mile Rock	talus slope	520	0.22	5	0.08	no	yes	yes	1%
7	11.2	R	A	Soap Creek	talus slope	33445	0.37	486	1.05	yes	yes	no	0%
8	11.2	R	B	Soap Creek	talus slope	16719	0.25	243	0.44	yes	yes	no	36%
9	11.2	R	C	Soap Creek	talus slope	43662	0.03	603	1.79	yes	no	yes	39%
10	44.8	L	A	Willy's Grave	debris lobe	803	0.07	13	0.25	yes	yes	yes	0%
11	51.7	R	A	Little Nankoweap	talus slope	5031	0.15	44	0.26	no	no	no	0%
12	51.7	R	B	Little Nankoweap	dune field	1	0.00	0	0.00	yes	yes	no	43%
13	51.8	R	C	Little Nankoweap	dune field	1	0.00	0	0.00	yes	yes	no	47%
14	51.8	R	D	Little Nankoweap	dune field	1	0.00	0	0.00	yes	yes	no	70%
15	51.8	R	E	Little Nankoweap	dune field	1	0.00	0	0.00	yes	yes	no	42%
16	52.2	R	F	Nankoweap	tributary plain	5287	0.13	46	0.17	yes	yes	yes	0%
17	52.3	R	G	Nankoweap	dune field	1	0.00	0	0.00	no	no	no	75%
18	52.3	R	H	Nankoweap	dune field	1	0.00	0	0.00	no	no	no	87%
19	52.3	R	I	Nankoweap	dune field	1	0.00	0	0.00	no	no	no	53%
20	52.5	R	K	Nankoweap	tributary plain	55188	0.23	551	0.93	yes	no	yes	0%
21	52.5	R	L	Nankoweap	talus slope	7609	0.05	67	0.51	no	no	no	0%
22	53.1	R	N	Nankoweap	alluvial fan	54976	0.11	1070	6.33	yes	yes	yes	0%
23	53.1	R	O	Nankoweap	alluvial fan	26852	0.00	489	0.63	yes	yes	yes	0%
24	53.1	R	P	Nankoweap	alluvial fan	129261	0.32	2456	5.54	no	yes	yes	0%
25	53.2	R	Q	Nankoweap	alluvial fan	1	0.09	0	0.00	no	yes	yes	0%
26	53.2	R	R	Nankoweap	alluvial fan	38733	0.05	452	1.11	no	yes	yes	0%
27	53.3	R	V	Nankoweap	talus slope	12842	0.06	206	2.49	no	yes	yes	0%
28	56.1	R	A	Kwagunt	tributary plain	34911	0.40	305	0.47	no	yes	no	10%
29	59.7	R	A	Sixty Mile	debris lobe	1147	0.03	22	0.26	no	no	yes	0%
30	59.7	R	B	Sixty Mile	debris lobe	795	0.03	15	0.35	yes	no	no	23%
31	65.2	L	A	Palisades	talus slope	5877	0.25	112	2.14	no	yes	yes	0%
32	65.2	L	B	Palisades	debris lobe	13557	0.35	198	0.51	no	yes	yes	0%

Summary of Catchment Data Used in Model *C.2*

Order	River Mile	River Side	Catch-ment	Location	x-sect. area 1st terr (m2)	cum vul mean	cum vul 1983	cum vul 1983	cum vul pda	cum vul lmt	cum vul umt	cum vul mt	cum vul ap	cum vul sa	cum vul ap/sa
				Grand Canyon											
1	1.1	R	A	Paria	16.87	20.3	0.0	0.0	0.0	25.0	25.0		51.6		
2	1.1	R	B	Paria	16.87	9.7	0.0	0.0	0.0	6.5	9.8		32.2		
3	2.0	L	A	Axe Handle Cove	33.00	90.2	85.3	85.3					85.3	100.0	
4	2.0	L	B	Axe Handle Cove	228.00	17.1	10.1	10.1						24.0	
5	2.0	L	C	Axe Handle Cove	289.14	73.6							73.6		
6	10.0	R	A	Ten Mile Rock	48.00	8.5	0.9	0.9	2.9			7.7	22.4		
7	11.2	R	A	Soap Creek	225.85	52.7	48.3	48.3				48.3	61.5		
8	11.2	R	B	Soap Creek	225.85	43.1	36.7	36.7				38.1	54.6		
9	11.2	R	C	Soap Creek	131.28	57.3			51.6			58.7	61.7		
10	44.8	L	A	Willy's Grave	149.27	7.6	0.5	0.5	1.4	3.2	10.0		23.1		
11	51.7	R	A	Little Nankoweap	160.74	18.7				6.2	12.1		17.2	39.4	
12	51.7	R	B	Little Nankoweap	19.20	0.0	0.0	0.0			0.0		0.0		
13	51.8	R	C	Little Nankoweap	32.00	0.0	0.0	0.0			0.0		0.0		
14	51.8	R	D	Little Nankoweap	32.00	0.0	0.0	0.0			0.0		0.0		
15	51.8	R	E	Little Nankoweap	32.00	0.0	0.0	0.0			0.0		0.0		
16	52.2	R	F	Nankoweap	46.00	20.1	4.8	4.7	9.5			17.9	47.7		
17	52.3	R	G	Nankoweap	5.30	0.0						0.0	0.0		
18	52.3	R	H	Nankoweap	5.30	0.0						0.0	0.0		
19	52.3	R	I	Nankoweap	5.30	0.0						0.0	0.0		
20	52.5	R	K	Nankoweap	197.44	64.6	64.6	64.6	64.6	64.6			64.6		
21	52.5	R	L	Nankoweap	96.00	27.7			9.8	29.6			43.8		
22	53.1	R	N	Nankoweap	83.20	87.9	87.9	87.9	87.9	87.9			87.9		
23	53.1	R	O	Nankoweap	180.00	0.0	0.0	43.6	43.6	52.0			57.9		
24	53.1	R	P	Nankoweap	270.00	71.5	58.2	74.8	74.8	74.8			74.8		
25	53.2	R	Q	Nankoweap	909.90	9.8	48.9	0.0	0.0	0.0			0.0	0.0	
26	53.2	R	R	Nankoweap	3780.00	21.9	16.9	16.9	16.9	16.9			20.8	38.1	
27	53.3	R	V	Nankoweap	100.00	38.4	32.0	32.0	32.0	32.0			32.0	64.0	
28	56.1	R	A	Kwagunt	120.00	51.3	44.1	44.1			44.1		65.7		
29	59.7	R	A	Sixty Mile	366.00	22.1	12.5	12.5	20.3	27.7			27.7		
30	59.7	R	B	Sixty Mile	366.00	16.3	6.0	6.0	11.4	23.8			23.8		
31	65.2	L	A	Palisades	157.20	42.1	37.7	37.7	37.7				50.8		
32	65.2	L	B	Palisades	34.00	81.4	78.2	78.2	78.2				87.7		

Summary of Catchment Data Used in Model

33	65.2	L	B'	Palisades	debris lobe	13557	0.57	198	0.51	no	yes	yes	0%
34	65.2	L	C	Palisades	debris lobe	1764	0.33	15	0.17	no	yes	yes	0%
35	65.2	L	D	Palisades	debris lobe	503	0.31	4	0.07	no	yes	yes	0%
36	65.3	R	A	Lava/Chuar	talus slope	1113	0.07	21	0.46	no	no	no	0%
37	65.3	R	B	Lava/Chuar	debris lobe	1612	0.04	28	0.53	no	no	no	0%
38	65.3	L	E	Palisades	debris lobe	4881	0.10	43	0.12	yes	yes	no	0%
39	65.5	L	F	Palisades	tributary plain	1035	0.25	9	0.13	yes	yes	no	0%
40	65.5	L	G	Palisades	tributary plain	133	0.10	1	0.05	yes	yes	no	0%
41	65.6	L	H	Palisades	tributary plain	144924	0.57	1779	14.58	yes	yes	yes	19%
42	65.6	L	H'	Palisades	tributary plain	52024	0.08	780	3.86	no	yes	yes	46%
43	66.9	L	A	Espejo Creek	talus slope	8770	1.00	77	1.45	no	yes	yes	0%
44	66.9	L	B	Espejo Creek	talus slope	6614	1.00	58	0.23	no	yes	yes	0%
45	67.0	L	E	Comanche Creek	tributary plain	1	0.15	0	0.00	yes	no	yes	0%
46	67.1	L	F	Comanche Creek	alluvial fan	180363	0.25	3002	1.54	no	no	yes	0%
47	67.3	L	H	Comanche Creek	alluvial fan	68882	0.00	849	0.64	yes	no	yes	0%
48	67.3	L	J	Comanche Creek	tributary plain	10721	0.21	94	0.29	no	no	yes	0%
49	67.8	L	K	Comanche Creek	talus slope	5405	0.14	106	0.76	yes	yes	yes	0%
50	68.9	L	A	Tanner	talus slope	1345	0.27	20	0.36	no	no	yes	10%
51	69.0	L	B	Tanner	talus slope	5136	0.21	57	0.25	no	yes	yes	0%
52	69.3	R	A	Basalt	dune field	8495	0.00	74	0.27	yes	yes	no	100%
53	69.3	R	B	Basalt	talus slope	679	0.21	9	0.22	no	yes	no	0%
54	69.3	R	C	Basalt	debris lobe	575	0.26	5	0.06	no	yes	no	0%
55	69.3	R	C'	Basalt	debris lobe	1	0.04	0	0.00	no	yes	no	0%
56	69.3	R	D	Basalt	debris lobe	769	0.00	7	0.11	yes	no	yes	0%
57	69.6	L	D	Lower Tanner	debris lobe	4122	0.19	36	0.09	yes	no	yes	0%
58	69.6	L	E	Lower Tanner	debris lobe	2017	0.19	18	0.09	yes	no	yes	32%
59	69.7	L	F	Lower Tanner	alluvial fan	53352	0.19	765	0.54	yes	no	yes	82%
60	70.2	L	A	Lower Tanner	dune field	18899	0.08	352	1.74	yes	no	no	63%
61	70.2	L	B	Lower Tanner	dune field	18899	0.17	352	1.74	yes	no	yes	63%
62	70.3	L	C	Lower Tanner	dune field	10938	0.31	96	0.90	yes	yes	yes	27%
63	71.5	R	A	Upper Unkar	talus slope	6240	0.10	118	2.21	yes	yes	yes	6%
64	71.5	R	B	Upper Unkar	talus slope	125	0.08	1	0.03	yes	yes	yes	0%
65	71.5	R	C	Upper Unkar	talus slope	1	0.05	0	0.00	yes	yes	yes	0%
66	71.5	R	D	Upper Unkar	talus slope	4618	0.05	82	1.47	yes	yes	yes	12%
67	71.6	R	E	Upper Unkar	talus slope	3994	0.10	66	1.10	yes	yes	yes	28%

Summary of Catchment Data Used in Model

33	65.2	L	B'	Palisades	64.60	66.4	63.8	63.8	63.8				71.5		
34	65.2	L	C	Palisades	46.00	19.0	8.4	5.2	12.5				33.0		
35	65.2	L	D	Palisades	46.00	7.9	1.3	0.8	3.7				17.9		
36	65.3	R	A	Lava/Chuar	16.00	64.7	55.6	55.6		69.2	69.2				
37	65.3	R	B	Lava/Chuar	84.00	26.5	17.8	17.8		20.4	27.1		40.6		
38	65.3	L	E	Palisades	58.20	30.0	15.5	15.5		28.3	46.1				
39	65.5	L	F	Palisades	22.00	19.9	4.7	4.7	9.7	32.6	32.6				
40	65.5	L	G	Palisades	22.00	0.6	0.0	0.0	0.0	0.2	2.3				
41	65.6	L	H	Palisades	142.50	64.3	28.8	71.4	71.4			71.4	78.6		
42	65.6	L	H'	Palisades	201.00	50.4	6.9	64.9	64.9				64.9		
43	66.9	L	A	Espejo Creek	123.90	24.3	15.5	15.4	15.6	18.7	28.9		42.5		
44	66.9	L	B	Espejo Creek	123.90	20.7	11.1	11.0	11.9	15.3	25.3		39.7		
45	67.0	L	E	Comanche Creek	123.00	0.0			0.0				0.0		
46	67.1	L	F	Comanche Creek	436.10	69.9			69.9						69.9
47	67.3	L	H	Comanche Creek	169.00	66.6			64.9	64.9	64.9				71.4
48	67.3	L	J	Comanche Creek	660.63	19.2			10.0	10.8	17.9		32.9		
49	67.8	L	K	Comanche Creek	31.68	43.1	24.5	24.5	35.4			35.4	40.9	79.3	
50	68.9	L	A	Tanner	2406.40	16.4			11.1					18.2	
51	69.0	L	B	Tanner	234.00	19.0	7.4	7.4	10.5	21.7				36.4	
52	69.3	R	A	Basalt	638.00	23.6	17.4	16.9							29.8
53	69.3	R	B	Basalt	81.00	18.6	10.5	11.0							26.7
54	69.3	R	C	Basalt	194.40	10.1	6.7	6.7					13.4		
55	69.3	R	C'	Basalt	194.40	0.0	0.0	0.0	0.0				0.0		
56	69.3	R	D	Basalt	129.00	10.2			3.0	9.0			18.5		
57	69.6	L	D	Lower Tanner	114.00	19.5			6.5	15.2	36.8				
58	69.6	L	E	Lower Tanner	88.00	21.5			12.1	21.1	31.3				
59	69.7	L	F	Lower Tanner	124.40	45.9			37.5	38.0	41.9		66.4		
60	70.2	L	A	Lower Tanner	3900.00	19.6			9.6			12.3	22.2	34.1	
61	70.2	L	B	Lower Tanner	2700.00	19.1			7.5			11.2	21.9	35.8	
62	70.3	L	C	Lower Tanner	3900.00	11.5	0.0	0.0	8.8				8.8	28.1	
63	71.5	R	A	Upper Unkar	372.00	28.2	0.0	31.2	38.6				42.9		
64	71.5	R	B	Upper Unkar	344.10	0.2	0.0	0.0	0.0				0.8		
65	71.5	R	C	Upper Unkar	279.00	0.0	0.0	0.0	0.0				0.0		
66	71.5	R	D	Upper Unkar	176.70	24.8	0.0	20.5	32.6				46.2		
67	71.6	R	E	Upper Unkar	372.00	22.2	0.2	21.1	29.8				37.6		

Summary of Catchment Data Used in Model *C.5*

68	71.6	R	F	Upper Unkar	talus slope	1955	0.09	29	0.36	yes	yes	yes	10%
69	71.6	R	G	Upper Unkar	talus slope	2247	0.09	35	0.37	yes	yes	yes	33%
70	71.6	R	H	Upper Unkar	talus slope	2579	0.09	34	0.35	yes	yes	yes	28%
71	72.2	R	A	Old Unkar Camp	talus slope	3321	0.18	66	0.68	yes	no	yes	80%
72	73.3	L	A	Lower Unkar	alluvial fan	19626	0.35	350	3.17	yes	yes	yes	10%
73	73.3	L	B	Lower Unkar	alluvial fan	30658	0.42	578	2.35	yes	no	yes	11%
74	73.4	L	C	Lower Unkar	alluvial fan	6363	0.36	133	0.33	yes	yes	yes	8%
75	121.9	R	A	122 Mile	debris lobe	144	0.01	2	0.12	yes	yes	no	0%
76	122.1	R	B	122 Mile	debris lobe	1596	0.05	24	0.74	no	no	yes	6%
77	122.1	R	C	122 Mile	debris lobe	394	0.03	7	0.17	yes	yes	no	15%
78	122.1	R	D	122 Mile	debris lobe	633	0.02	10	0.28	yes	yes	no	11%
79	134.5	R	A	Owl Eyes	dune field	6280	0.08	35	0.45	no	no	no	0%
80	134.5	R	A'	Owl Eyes	dune field	12016	0.10	68	0.55	no	no	no	0%
81	134.6	L	B	Owl Eyes	debris lobe	44	0.04	0	0.03	yes	no	yes	32%
82	134.6	L	B'	Owl Eyes	debris lobe	142	0.04	1	0.04	yes	no	yes	100%
83	139.0	R	A	Fishtail	debris lobe	1518	0.03	13	0.37	no	no	yes	14%
84	139.7	L	A	140 Mile	debris lobe	2449	0.02	21	0.24	no	yes	yes	27%
85	176.3	R	A	Saddle Horse	debris lobe	6062	0.13	57	0.93	yes	no	yes	5%
86	176.4	R	B	Saddle Horse	debris lobe	1183	0.01	10	0.22	no	yes	yes	0%
87	182.7	R	A	183 Mile	debris lobe	102	0.03	1	0.04	no	no	no	0%
88	186.2	L	A	186 Mile	dune field	2527	0.08	22	0.65	no	yes	yes	47%
89	189.7	L	A	190 Mile	debris lobe	20027	0.03	313	1.98	no	no	no	0%
90	194.4	L	A	194 Mile	tributary plain	27280	0.17	346	4.47	yes	yes	yes	0%
91	196.2	R	A	196 Mile	talus slope	2229	0.02	47	1.21	yes	yes	yes	0%
92	201.1	R	A	201 Mile	debris lobe	8206	0.30	152	1.70	yes	yes	yes	0%
93	201.1	R	B	201 Mile	debris lobe	2899	0.12	55	0.41	yes	yes	yes	0%
94	201.2	R	C	201 Mile	debris lobe	2899	0.17	55	0.43	yes	yes	yes	0%
95	201.2	R	D	201 Mile	debris lobe	2899	0.06	55	0.43	yes	yes	yes	0%
96	201.3	R	E	201 Mile	debris lobe	780	0.13	7	0.63	yes	no	no	0%
97	201.8	R	A	202 Mile	debris lobe	8650	0.24	128	2.81	yes	no	no	6%
98	201.9	R	B	202 Mile	debris lobe	339	0.03	3	0.61	no	yes	no	25%
99	206.5	R	A	Indian Canyon	talus slope	280	0.02	6	0.04	no	no	no	0%
100	206.6	R	B	Indian Canyon	talus slope	669	0.06	14	0.39	no	no	no	0%
101	207.6	L	A	Arroyo Grande	alluvial fan	104048	1.00	1340	2.31	yes	yes	no	0%
102	207.7	L	A'	Arroyo Grande	alluvial fan	697	0.23	6	0.13	yes	yes	yes	0%

Summary of Catchment Data Used in Model

68	71.6	R	F	Upper Unkar	195.30	21.9	0.3	20.2	32.7				34.4		
69	71.6	R	G	Upper Unkar	186.00	23.1	0.3	18.4	36.9				36.9		
70	71.6	R	H	Upper Unkar	186.00	23.9	0.4	21.9	36.6				36.6		
71	72.2	R	A	Old Unkar Camp	433.17	27.8			22.6			24.1		36.6	
72	73.3	L	A	Lower Unkar	1277.48	38.9	33.3	33.3	37.3			42.5		42.5	
73	73.3	L	B	Lower Unkar	1277.48	44.7	42.6	42.6	43.9			46.1		46.1	
74	73.4	L	C	Lower Unkar	1277.48	28.6	18.9	18.9	25.3			34.6		35.5	
75	121.9	R	A	122 Mile	201.60	3.3	0.1	0.1				0.8	8.9		
76	122.1	R	B	122 Mile	280.00	20.6			13.0				30.0		
77	122.1	R	C	122 Mile	362.34	12.3	7.5	7.6					17.4		
78	122.1	R	D	122 Mile	299.97	15.0	9.1	9.3					21.3		
79	134.5	R	A	Owl Eyes	353.81	16.6							28.8		
80	134.5	R	A'	Owl Eyes	272.21	22.9							35.6		
81	134.6	L	B	Owl Eyes	60.79	0.0	0.0	0.0	0.0	0.0			0.0		
82	134.6	L	B'	Owl Eyes	67.80	0.6	0.0	0.0	0.0	0.1			2.4		
83	139.0	R	A	Fishtail	148.74	10.3	1.1	1.2	3.8			8.9			27.4
84	139.7	L	A	140 Mile	261.00	18.6	7.2	7.2	19.1			19.1			28.8
85	176.3	R	A	Saddle Horse	136.29	31.6			22.7			27.1	45.0		
86	176.4	R	B	Saddle Horse	637.67	10.9			7.4			7.9			17.3
87	182.7	R	A	183 Mile	209.25	0.0			0.0			0.0			0.0
88	186.2	L	A	186 Mile	459.00	6.8	1.5	2.0	2.9			6.5			21.0
89	189.7	L	A	190 Mile	328.32	43.7				41.3	41.3		42.7	52.9	
90	194.4	L	A	194 Mile	719.28	37.1	33.5	33.5	33.5	33.5	38.2				46.7
91	196.2	R	A	196 Mile	29.76	26.7	0.3	9.7	20.4			36.0	67.1		
92	201.1	R	A	201 Mile	106.27	31.2	0.0	0.0	30.3	30.3	35.8				59.5
93	201.1	R	B	201 Mile	106.27	20.2	0.0	0.0	15.3	15.3	22.7				47.4
94	201.2	R	C	201 Mile	106.27	20.2	0.0	0.0	15.3	15.3	22.7				47.4
95	201.2	R	D	201 Mile	106.27	20.2	0.0	0.0	15.3	15.3	22.7				47.4
96	201.3	R	E	201 Mile	106.27	13.0					5.1				21.0
97	201.8	R	A	202 Mile	389.50	36.8	23.9	23.9				43.2			43.2
98	201.9	R	B	202 Mile	426.56	4.4	0.9	0.9					7.9		
99	206.5	R	A	Indian Canyon	383.73	10.0					4.5				15.5
100	206.6	R	B	Indian Canyon	287.90	16.4					8.5				24.3
101	207.6	L	A	Arroyo Grande	609.00	59.2	59.2	59.2				59.2			59.2
102	207.7	L	A'	Arroyo Grande	297.45	5.0	0.3	0.3	0.8			3.3			15.5

Summary of Catchment Data Used in Model

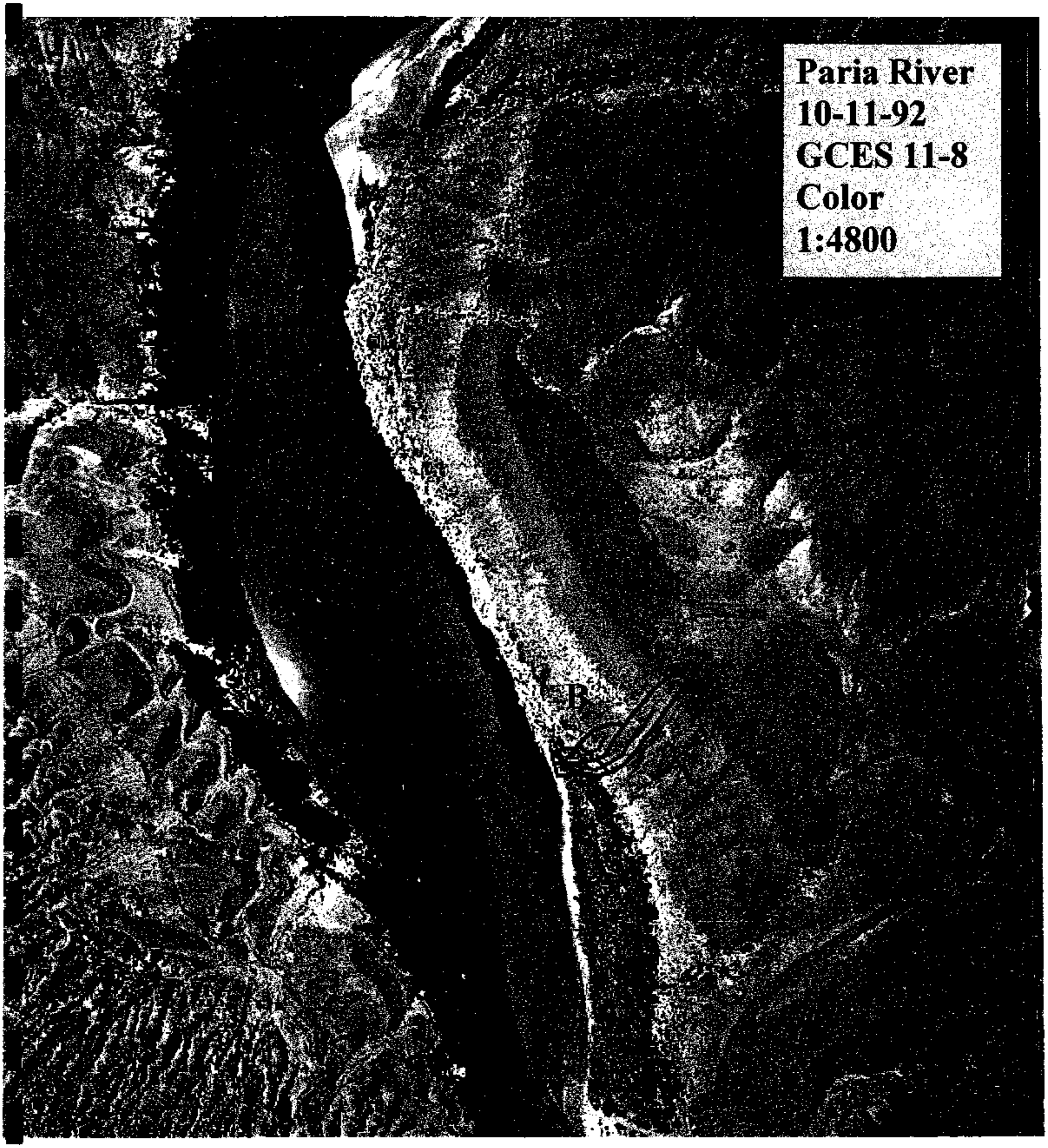
103	207.7	L	B	Arroyo Grande	alluvial fan	2640	0.23	23	0.18	no	yes	yes	0%
104	207.8	L	C	Arroyo Grande	debris lobe	3114	0.38	27	0.08	no	yes	no	0%
105	207.8	L	D	Arroyo Grande	debris lobe	1578	0.42	14	0.10	yes	yes	no	0%
106	207.8	L	E	Arroyo Grande	debris lobe	244	0.15	2	0.11	yes	yes	no	0%
107	208.5	L	A	Granite Park	tributary plain	31948	0.64	426	2.01	no	yes	yes	0%
108	208.6	L	B	Granite Park	tributary plain	1288	0.13	11	0.04	yes	no	yes	0%
109	208.6	L	B'	Granite Park	tributary plain	602	0.03	5	0.02	yes	no	yes	0%
110	208.7	L	D	Granite Park	tributary plain	26041	0.12	450	1.46	yes	no	yes	2%
111	208.7	L	D'	Granite Park	tributary plain	1	0.00	0	0.00	yes	no	yes	2%
112	208.8	L	E	Granite Park	tributary plain	131785	0.88	2565	2.33	no	no	no	5%
113	208.8	L	F	Granite Park	tributary plain	19669	0.81	172	0.56	no	no	no	5%
114	208.9	L	G	Granite Park	dune field	1	0.02	0	0.00	no	yes	no	0%
115	209.1	L	H	Granite Park	dune field	27281	0.25	489	1.73	no	no	yes	1%
116	209.3	R	A	209 Mile	talus slope	19769	0.19	351	1.68	no	no	no	0%
117	209.4	R	B	209 Mile	talus slope	19769	0.42	357	2.85	no	no	no	0%
118	209.4	R	C	209 Mile	talus slope	595	0.17	5	0.12	no	no	yes	0%
119	212.0	R	A	Fall Canyon	debris lobe	2299	0.07	25	0.55	yes	yes	yes	4%
				Cataract Canyon									
120	-211.1	L	A	Rapid 4	alluvial fan	1	0.04	0	0.00	yes	yes	yes	0%
121	-211.1	L	B	Rapid 4	alluvial fan	1	0.02	0	0.00	yes	yes	yes	0%
122	-211.1	L	C	Rapid 4	alluvial fan	10222	0.05	217	1.36	yes	yes	yes	0%
123	-208.3	L	A	Cross Canyon	alluvial fan	23555	0.18	378	1.45	yes	yes	yes	0%
124	-208.3	L	B	Cross Canyon	alluvial fan	22666	0.19	415	0.97	yes	yes	yes	0%
125	-206.6	L	B	Rapid 12	talus slope	66665	0.16	1396	3.75	no	yes	yes	0%
126	-206.6	L	C	Rapid 12	talus slope	66665	0.19	1396	3.75	no	yes	yes	0%
127	-206.6	L	D	Rapid 12	talus slope	94665	0.12	1956	2.00	no	yes	yes	0%

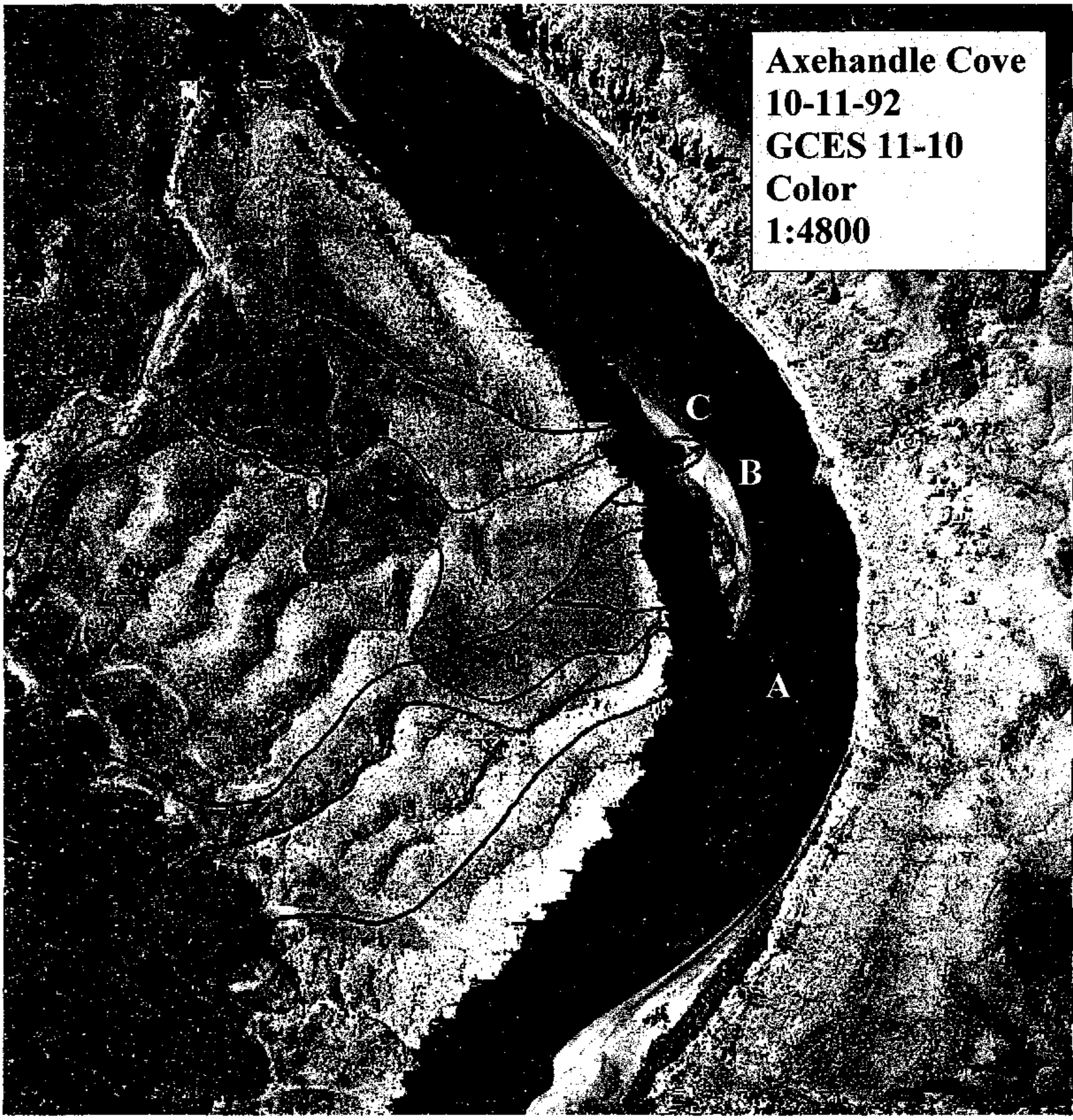
Summary of Catchment Data Used in Model

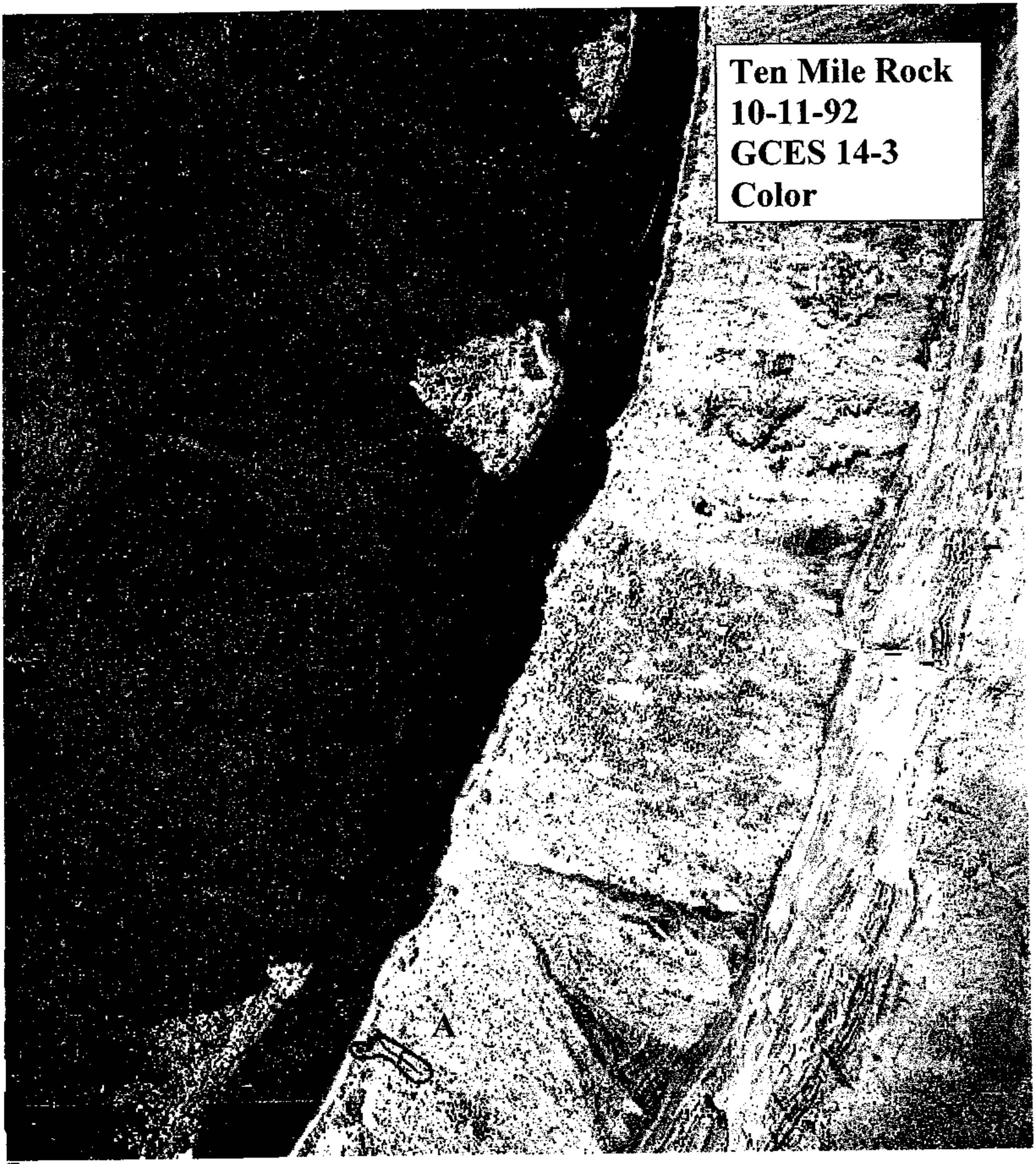
														C.8
103	207.7	L	B	Arroyo Grande	297.45	11.2	2.9	2.7	4.8			9.8		26.8
104	207.8	L	C	Arroyo Grande	137.25	22.6	12.7	12.7						32.5
105	207.8	L	D	Arroyo Grande	137.25	16.9	8.0	8.0						25.8
106	207.8	L	E	Arroyo Grande	137.25	4.0	0.6	0.6						7.4
107	208.5	L	A	Granite Park	162.40	36.2	21.0	21.0	33.2	33.2	42.0		51.8	
108	208.6	L	B	Granite Park	172.80	8.4			1.4	3.1	7.6			21.4
109	208.6	L	B'	Granite Park	172.80	4.9			0.3	1.0	3.6			14.7
110	208.7	L	D	Granite Park	720.30	23.1	14.1	12.7	14.3	17.3	28.5			41.1
111	208.7	L	D'	Granite Park	720.30	0.0	0.0	0.0	0.0	0.0	0.0			0.0
112	208.8	L	E	Granite Park	70.40	86.1				86.1	86.1			
113	208.8	L	F	Granite Park	70.40	45.8				35.1	56.5			
114	208.9	L	G	Granite Park	3427.20	0.0	0.0	0.0				0.0		0.0
115	209.1	L	H	Granite Park	648.00	44.0	40.3	40.3	40.3	40.3	49.7			49.7
116	209.3	R	A	209 Mile	111.09	43.8	7.9	42.6				56.2	68.6	
117	209.4	R	B	209 Mile	124.55	64.1			59.7			65.7	66.9	
118	209.4	R	C	209 Mile	110.40	8.9			1.3			6.2	19.3	
119	212.0	R	A	Fall Canyon	461.55	14.3	4.8	4.8	12.9					25.0
				Cataract Canyon										
120	-211.1	L	A	Rapid 4	400.00	0.0		0.0	0.0			0.0	0.0	
121	-211.1	L	B	Rapid 4	400.00	0.0		0.0	0.0			0.0	0.0	
122	-211.1	L	C	Rapid 4	400.00	41.5		41.5	41.5			41.5	41.5	
123	-208.3	L	A	Cross Canyon	250.00	51.3		51.3	51.3			51.3	51.3	
124	-208.3	L	B	Cross Canyon	250.00	52.1		52.1	52.1			52.1	52.1	
125	-206.6	L	B	Rapid 12	220.00	61.0		61.0	61.0			61.0	61.0	
126	-206.6	L	C	Rapid 12	220.00	61.0		61.0	61.0			61.0	61.0	
127	-206.6	L	D	Rapid 12	220.00	63.9		63.9	63.9			63.9	63.9	

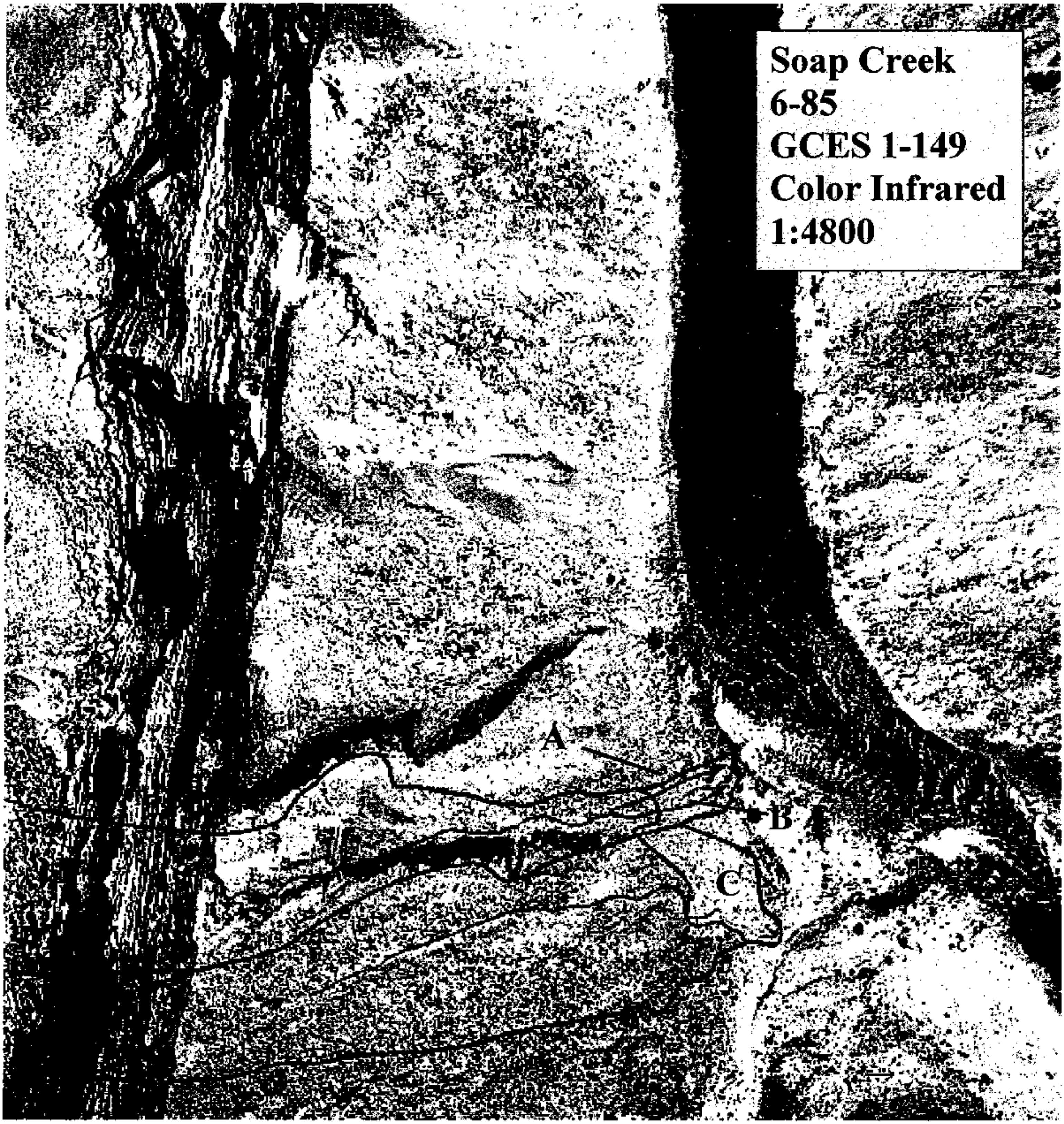
APPENDIX D

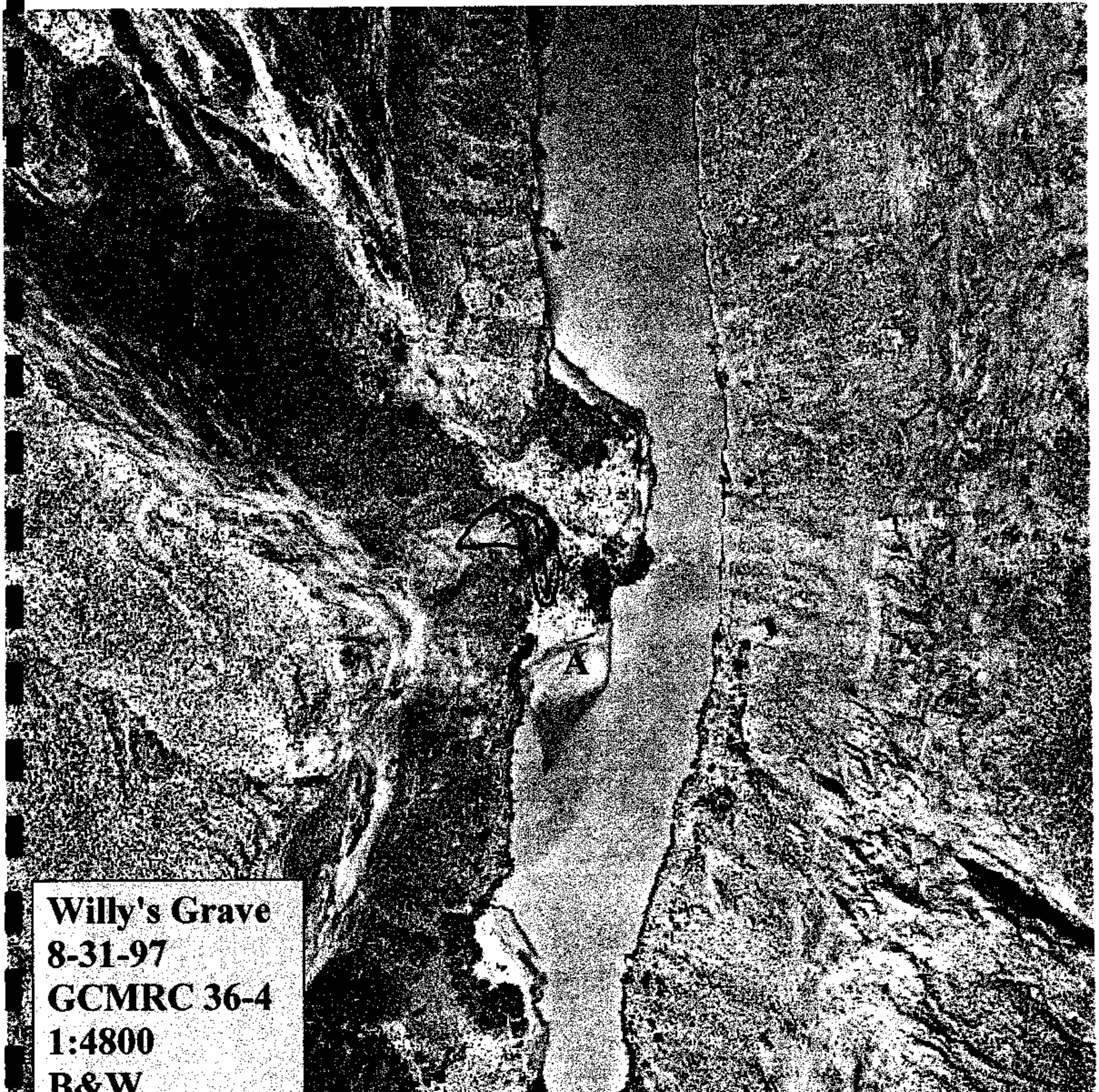
AIR PHOTOS OF GRAND CANYON CATCHMENT AREAS


Paria River
10-11-92
GCES 11-8
Color
1:4800
P

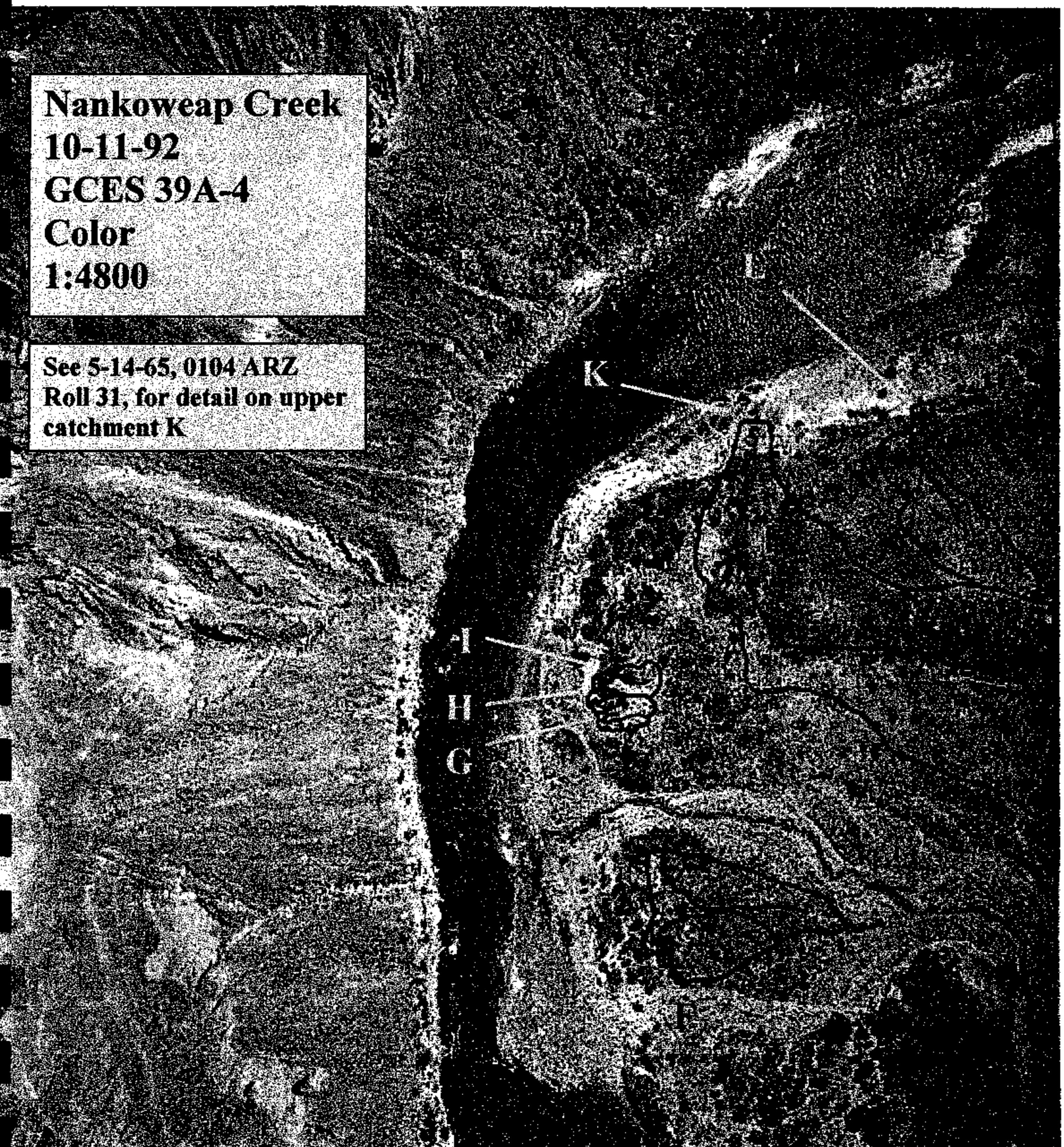

Axehandle Cove
10-11-92
GCES 11-10
Color
1:4800
C
B
A

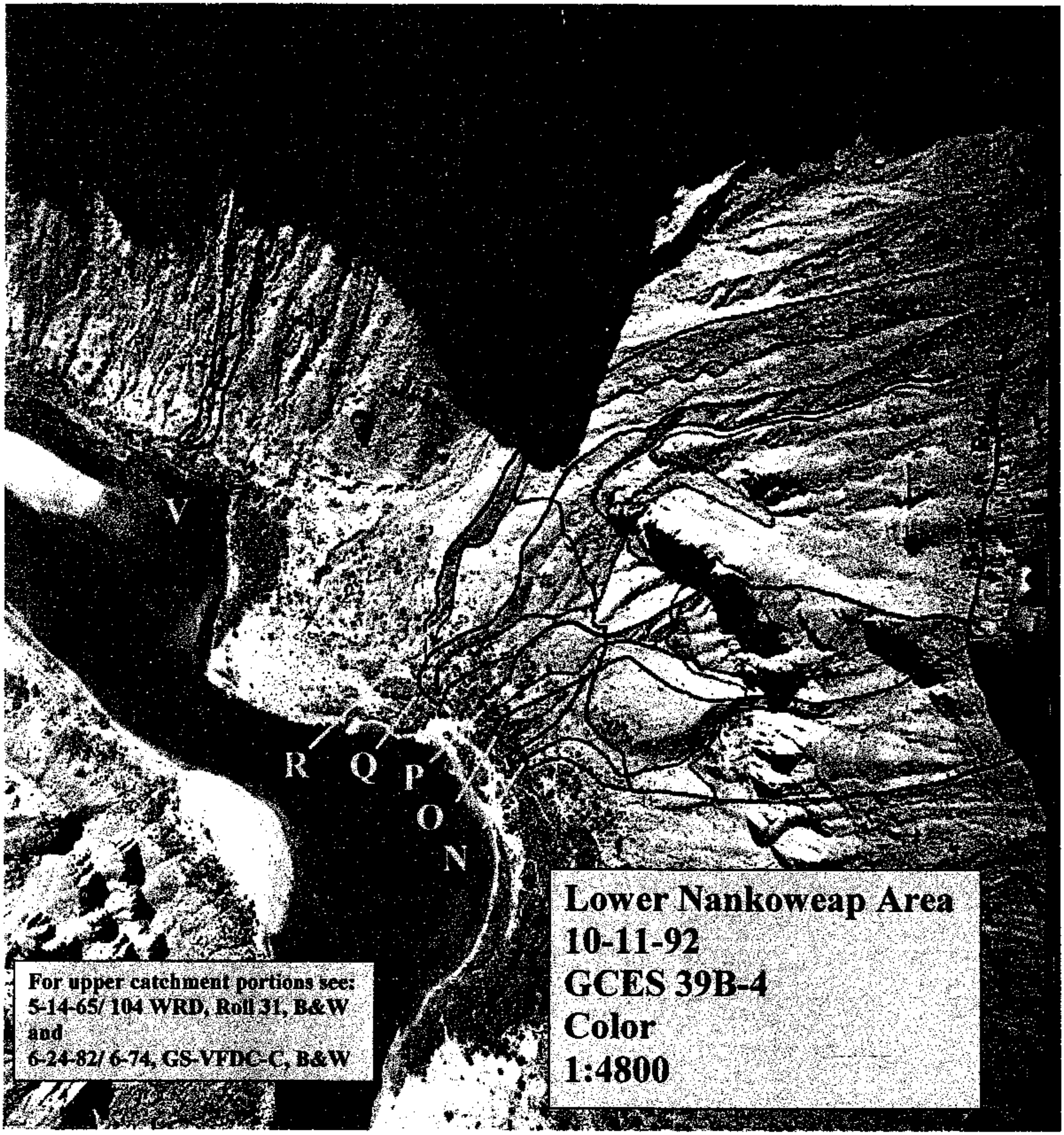

Ten Mile Rock
10-11-92
GCES 14-3
Color
A

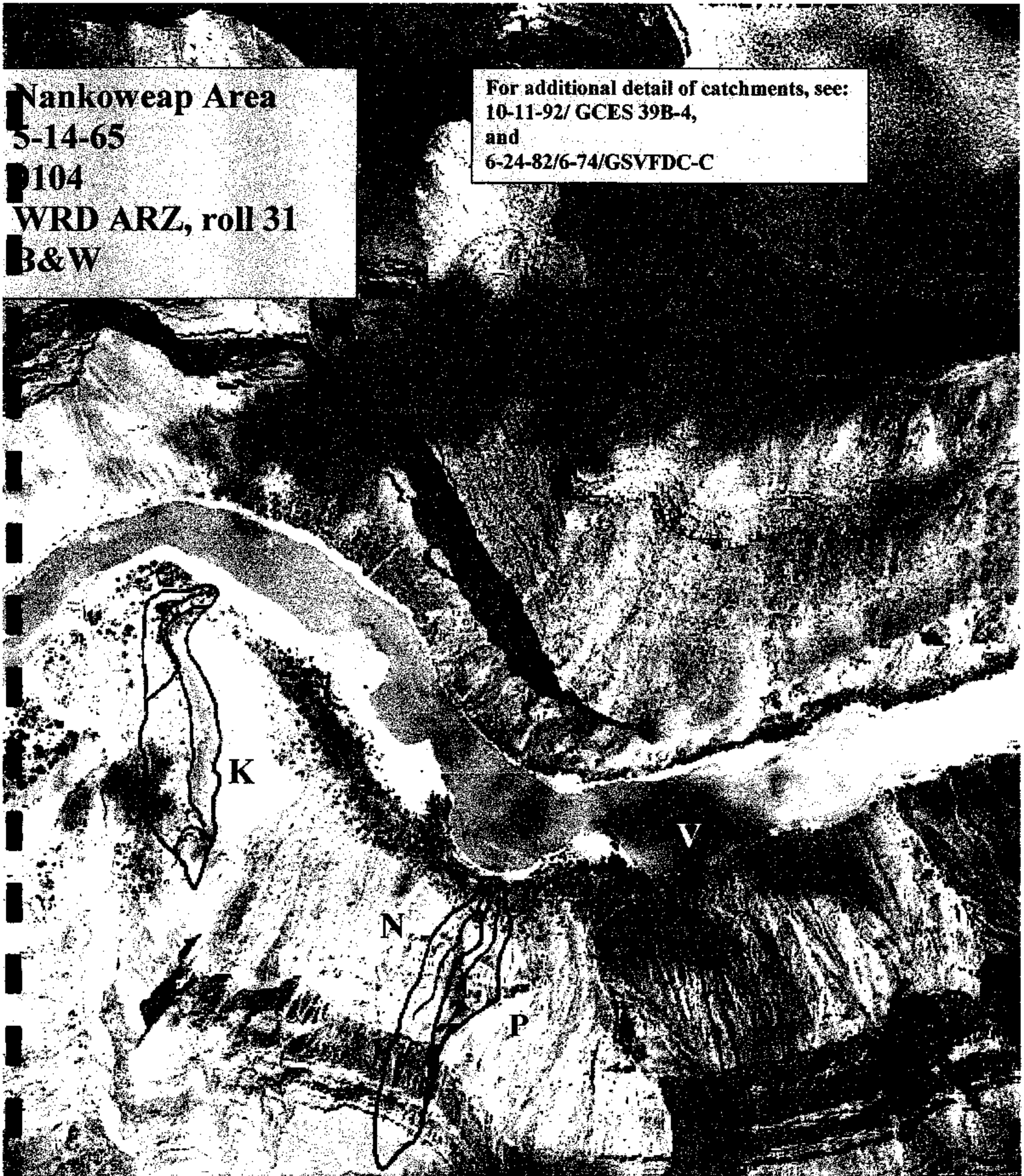

Soap Creek
6-85
GCES 1-149
Color Infrared
1:4800
A
B
C

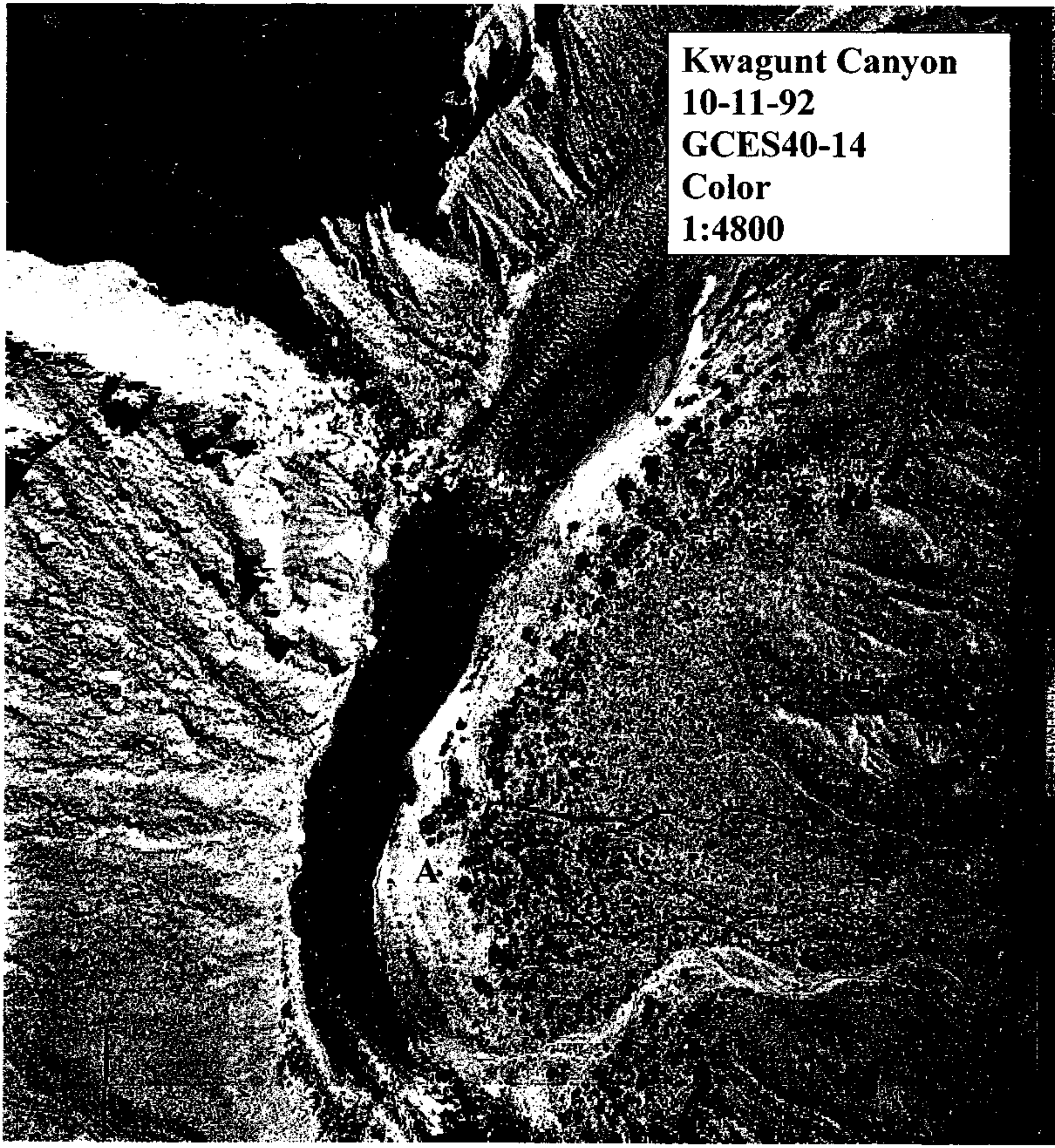

A
Willy's Grave
8-31-97
GCMRC 36-4
1:4800
B&W

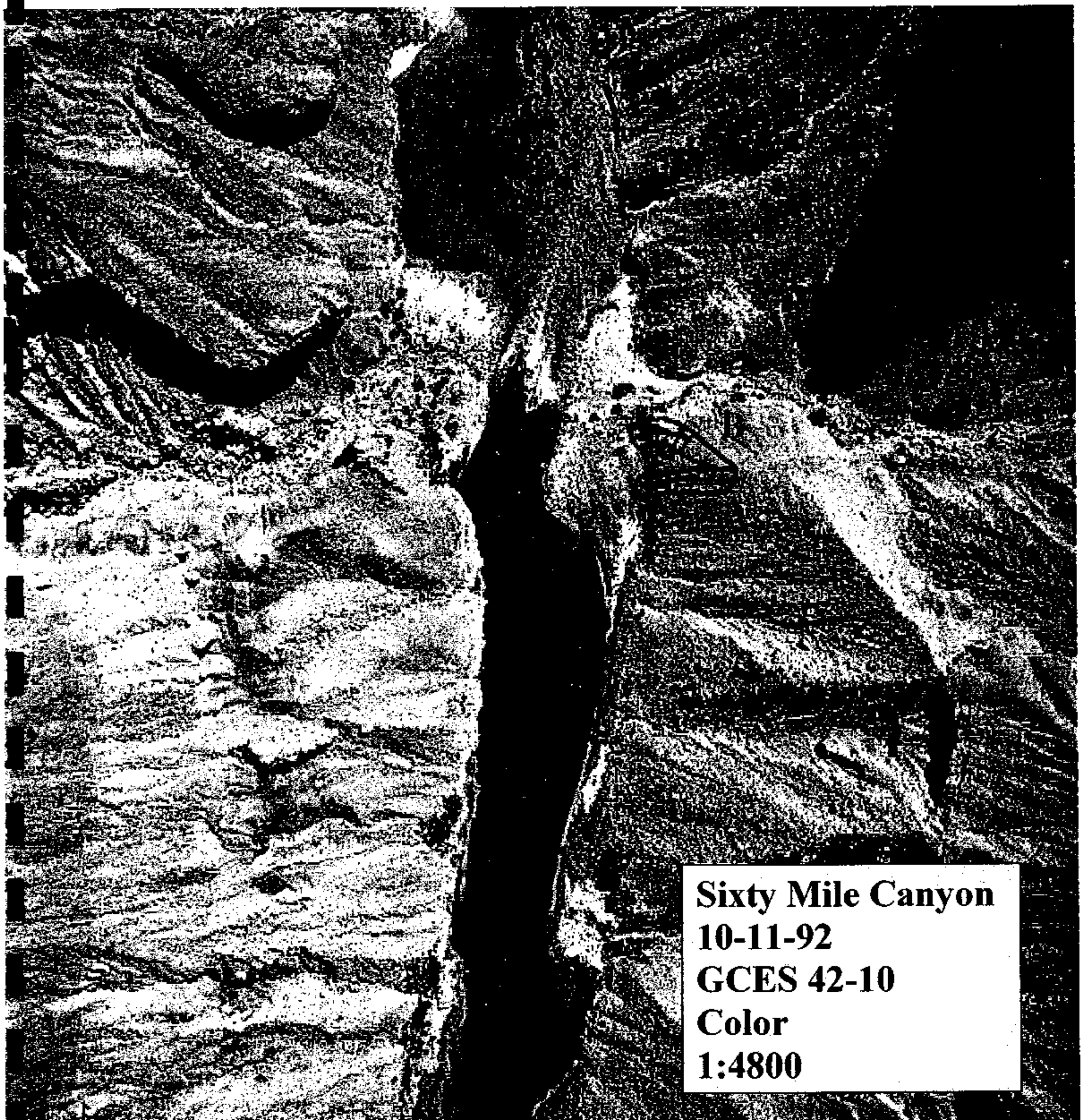

Little Nankoweap
10-11-92
GCES 39A-2
Color
1:4800
E
D
C
B
A

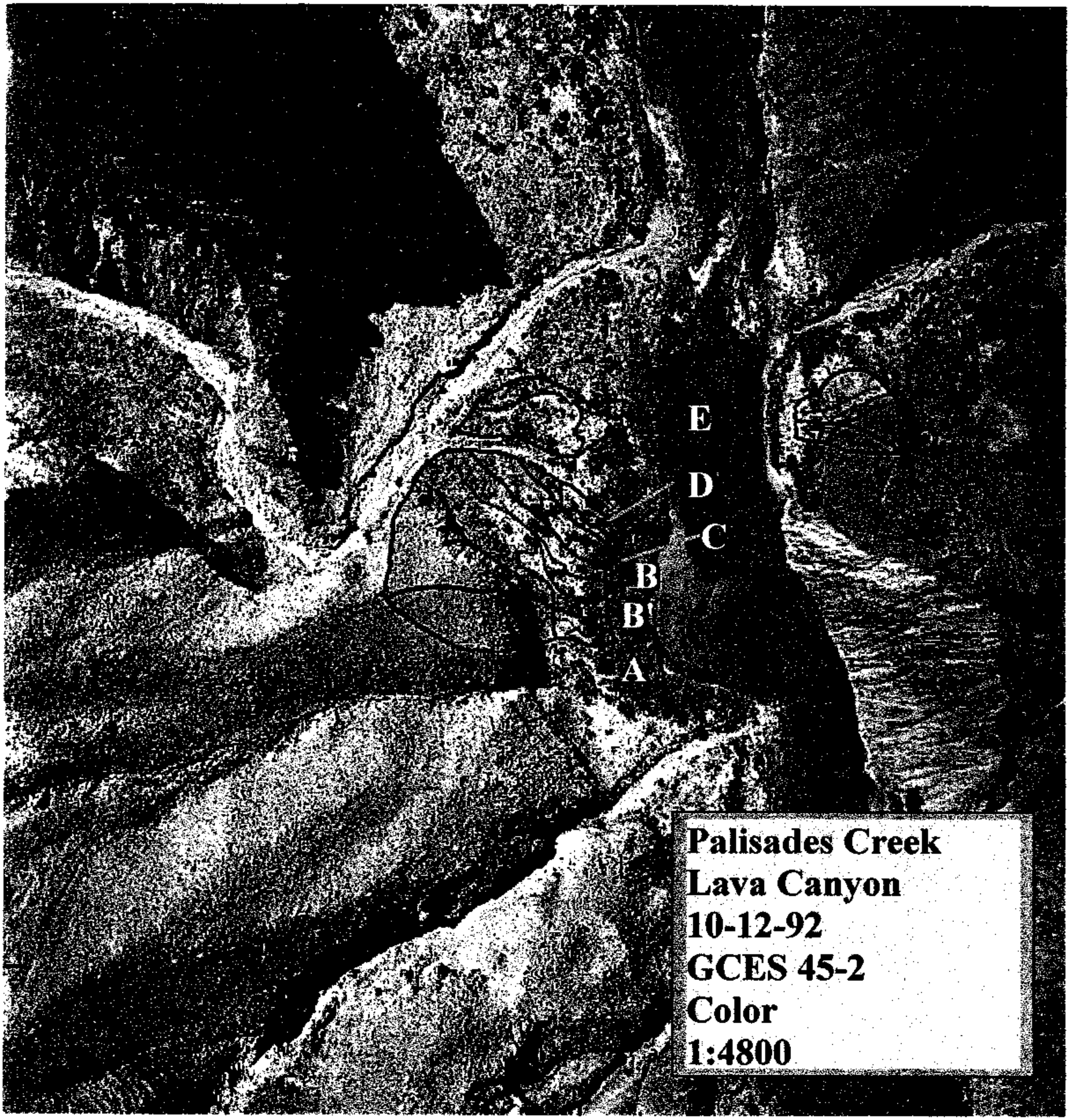

Nankoweap Creek
10-11-92
GCES 39A-4
Color
1:4800
See 5-14-65, 0104 ARZ
Roll 31, for detail on upper
catchment K
K
I
H
G

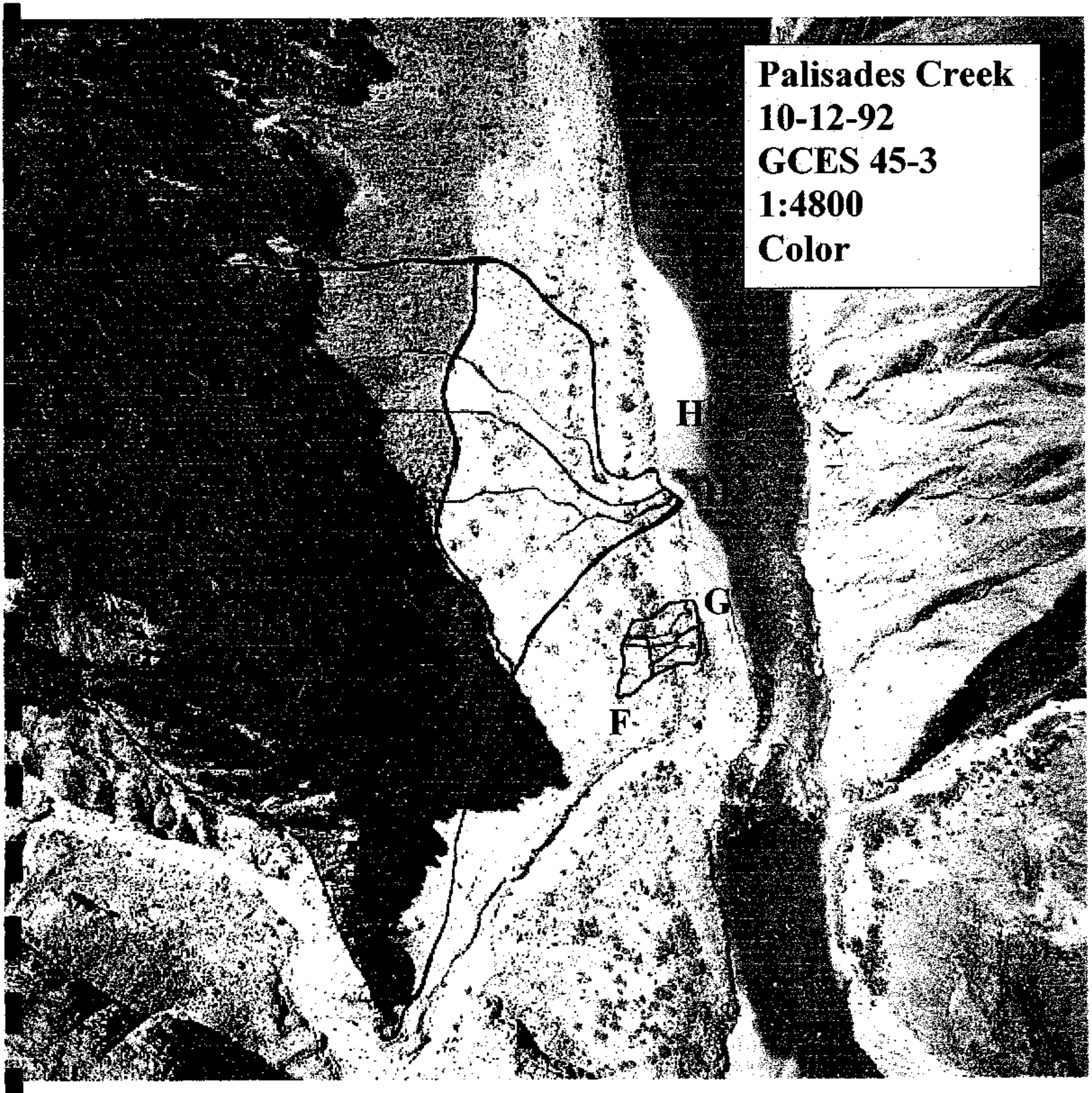

V
R
Q
P
O
N
Lower Nankoweap Area
10-11-92
GCES 39B-4
Color
1:4800
For upper catchment portions see:
5-14-65/ 104 WRD, Roll 31, B&W
and
6-24-82/ 6-74, GS-VFDC-C, B&W

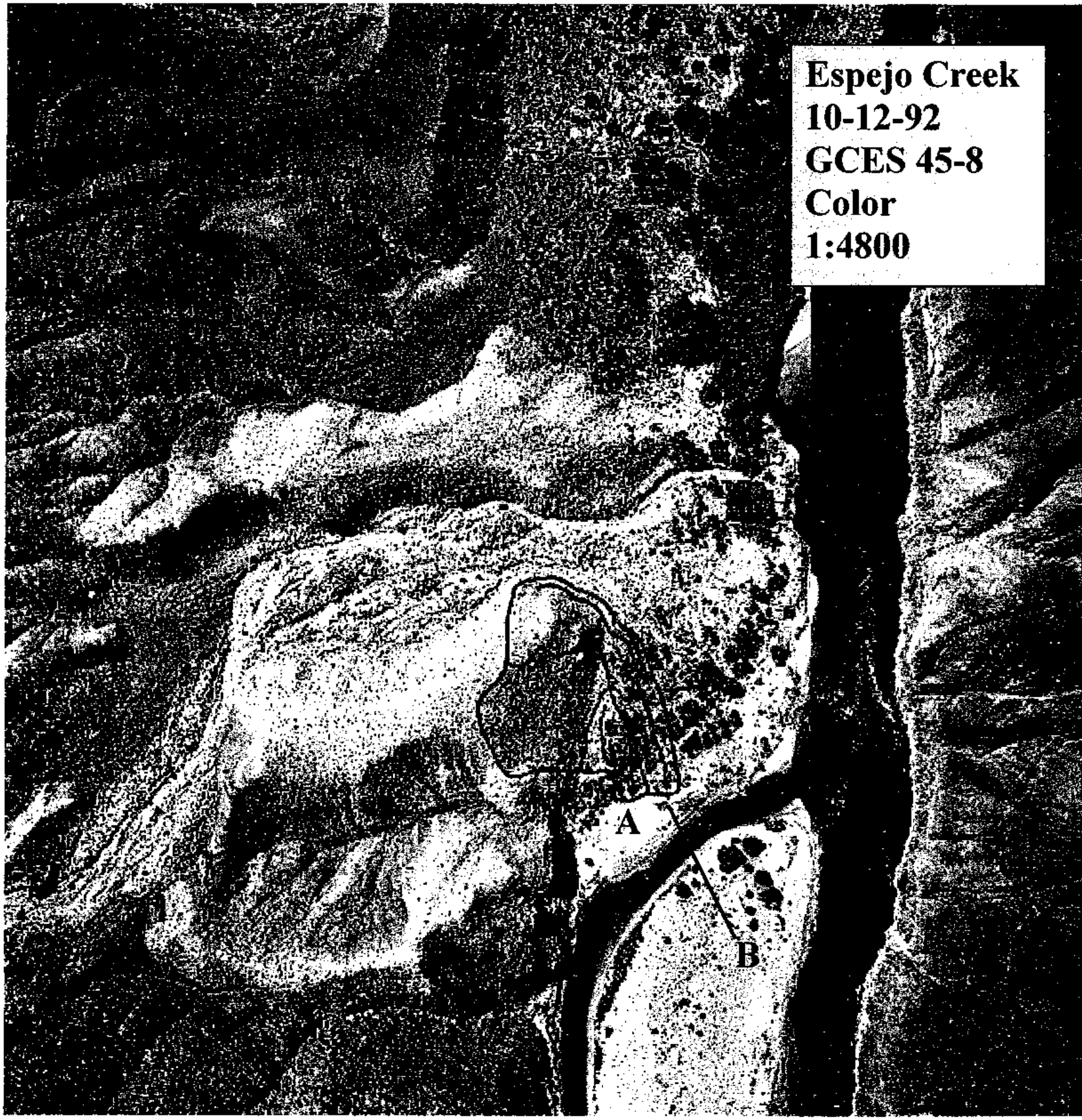

Nankoweap Area
5-14-65
104
WRD ARZ, roll 31
B&W
For additional detail of catchments, see:
10-11-92/ GCES 39B-4,
and
6-24-82/6-74/GSVFDC-C
K
V
N
P

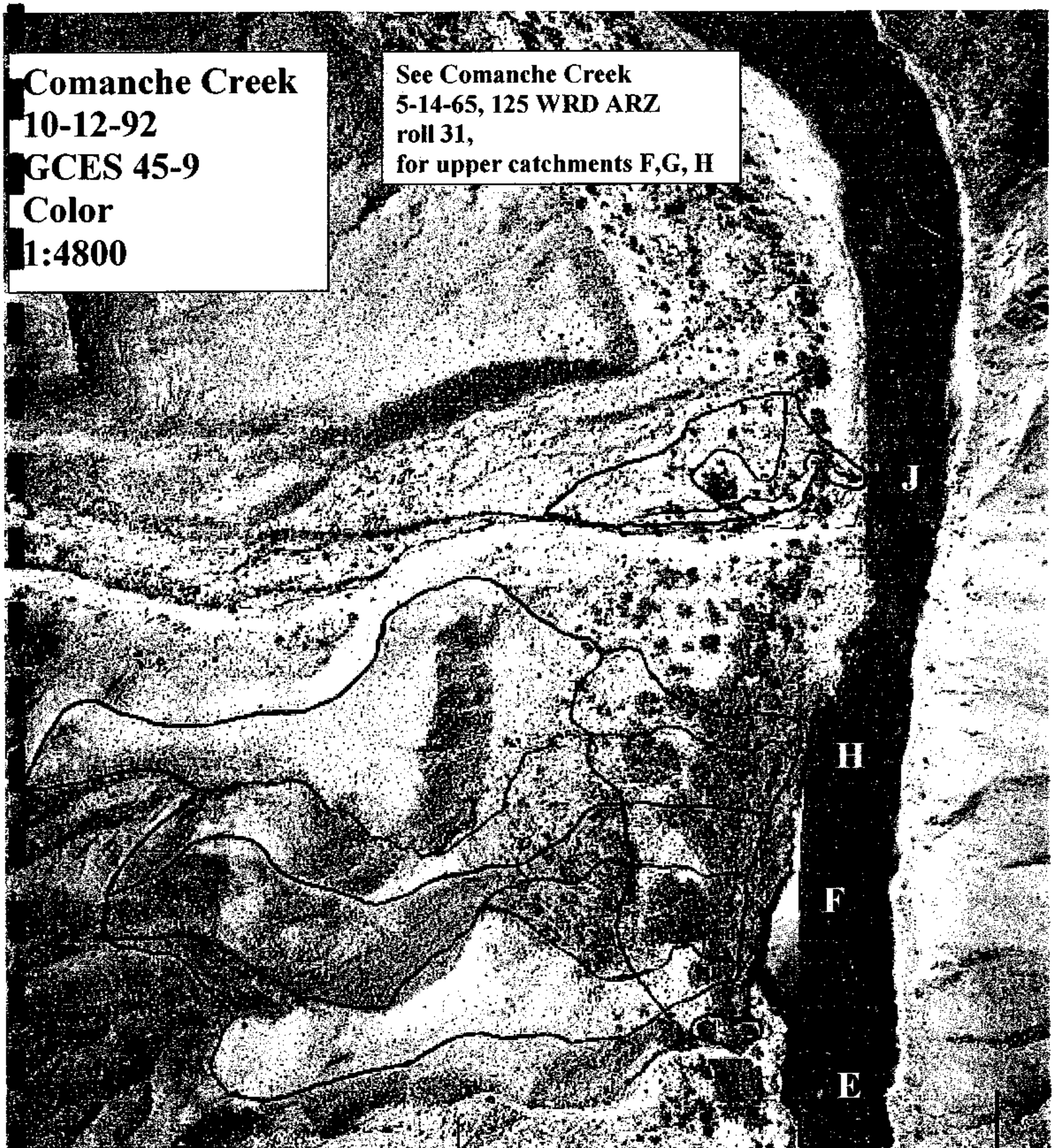

Kwagunt Canyon
10-11-92
GCES40-14
Color
1:4800
A


Sixty Mile Canyon
10-11-92
GCES 42-10
Color
1:4800


E
D
C
B
B'
A
Palisades Creek
Lava Canyon
10-12-92
GCES 45-2
Color
1:4800


Palisades Creek
10-12-92
GCES 45-3
1:4800
Color
H
G
F

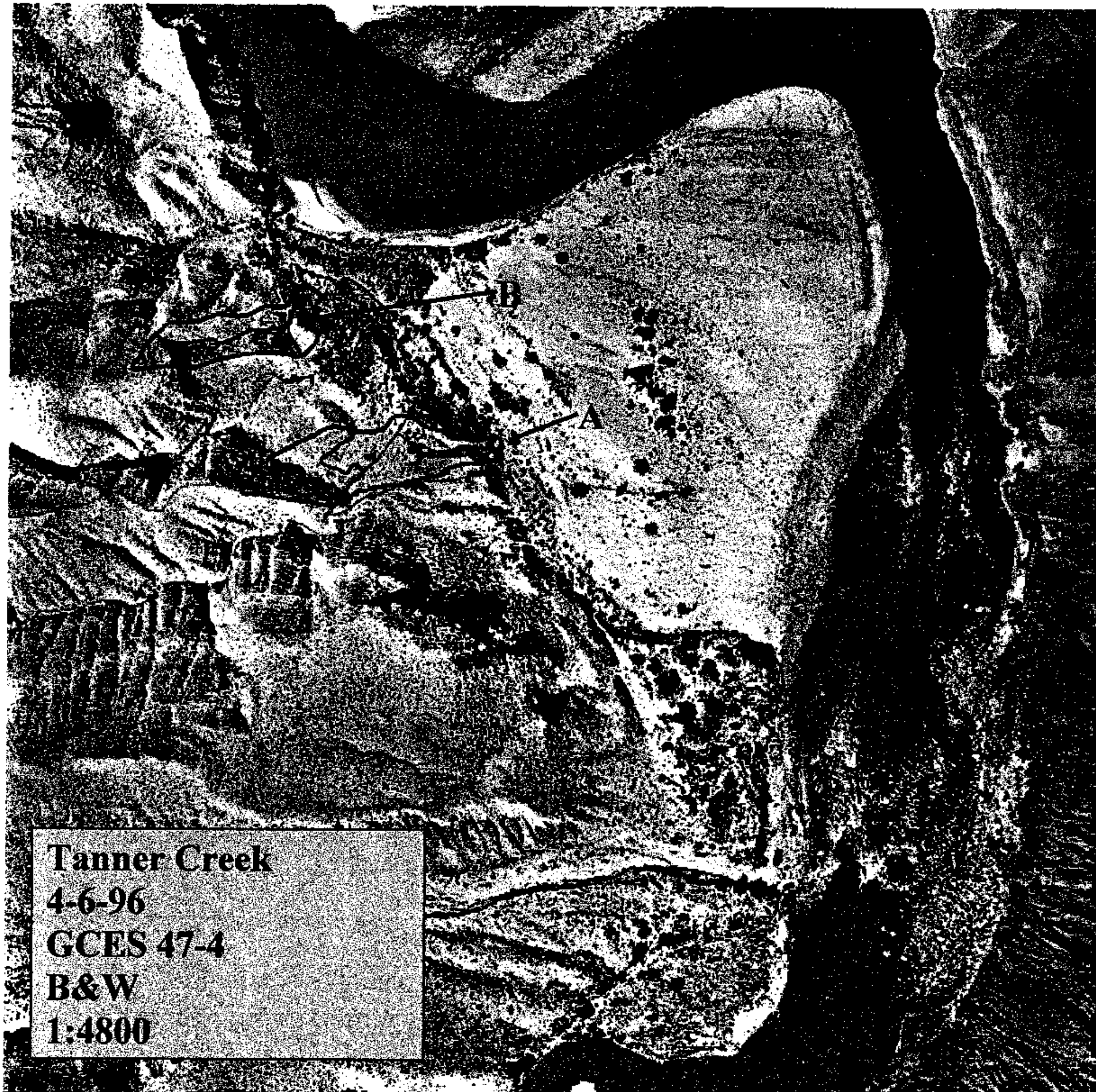

Espejo Creek
10-12-92
GCES 45-8
Color
1:4800
A
B

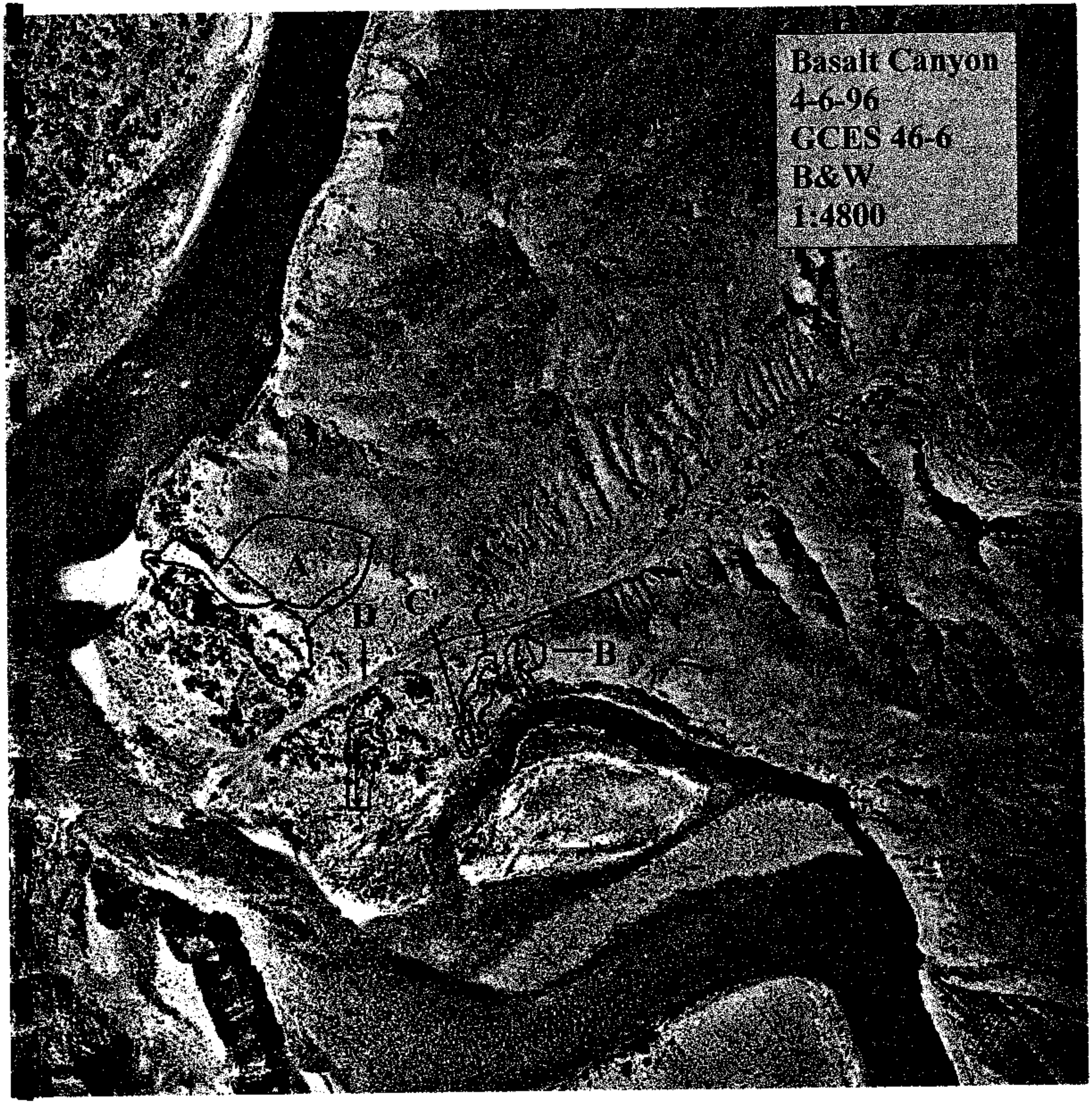


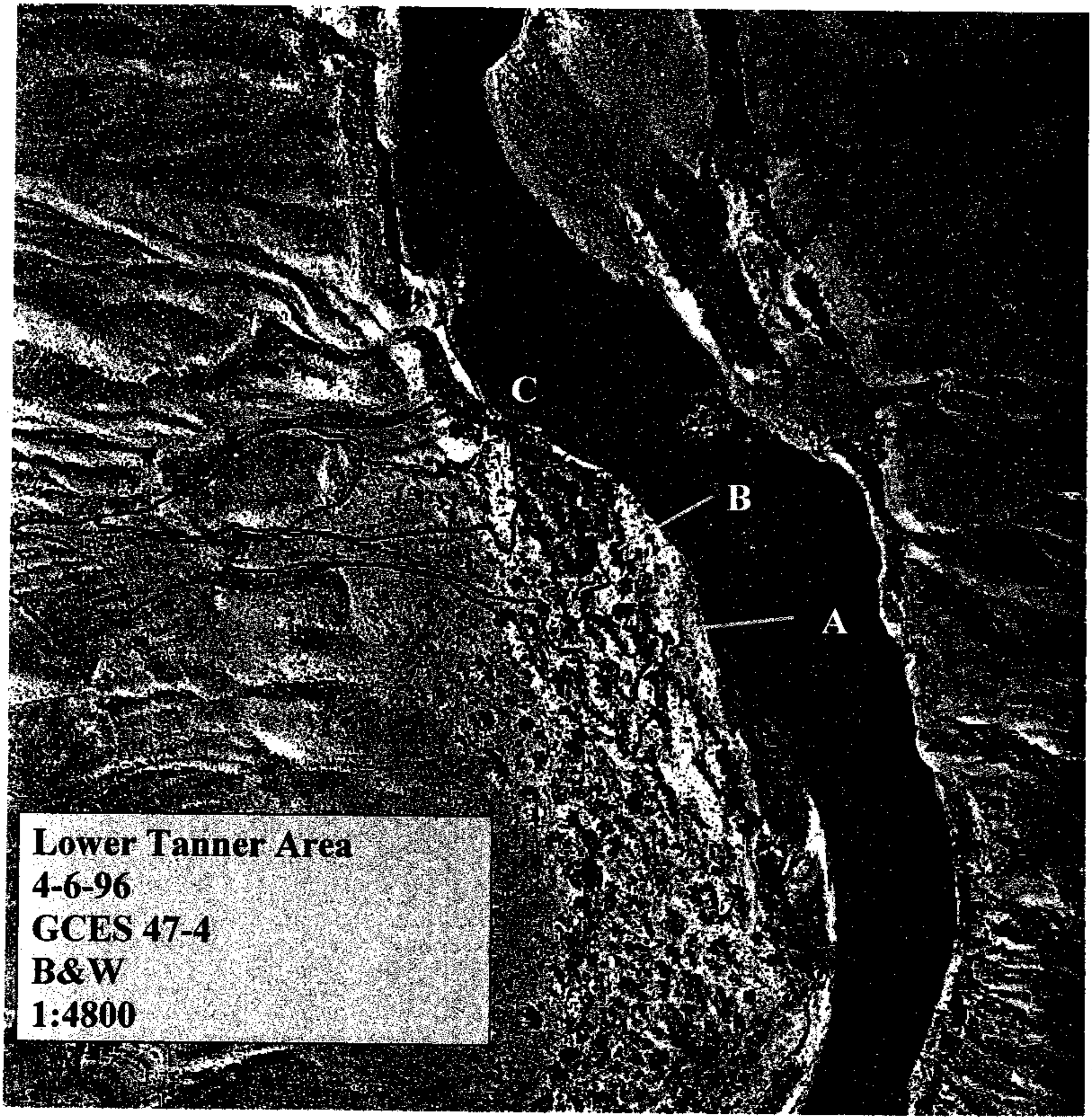
Comanche Creek
10-12-92
GCES 45-9
Color
1:4800
See Comanche Creek
5-14-65, 125 WRD ARZ
roll 31,
for upper catchments F,G, H
J
H
F
E

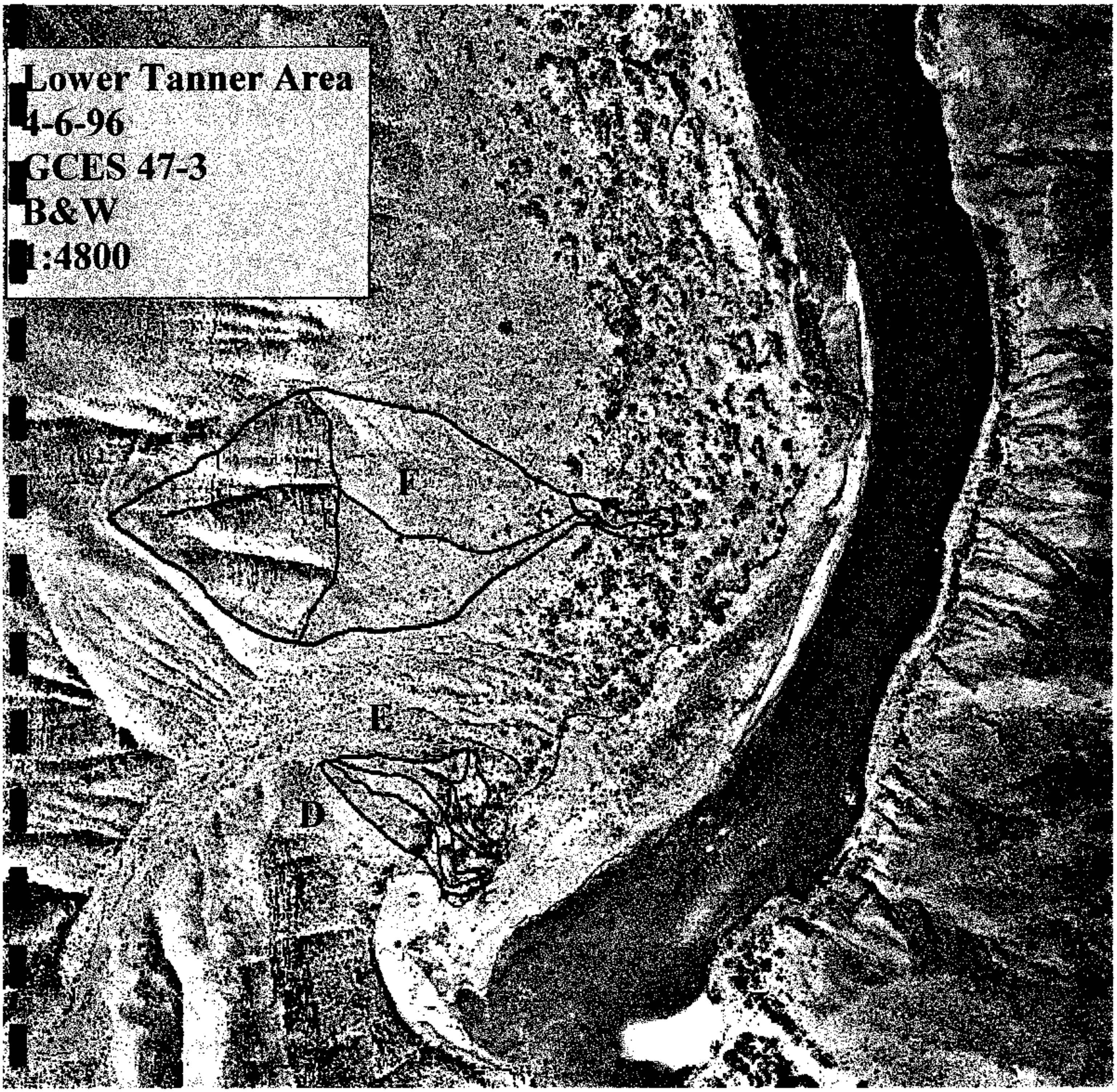

Comanche Creek
5-14-65
125 WRD ARZ, roll 31
1:12000
See 10-12-92 GCES 45-9, 1:4800
for detail on lower catchments F,G, H
F
H

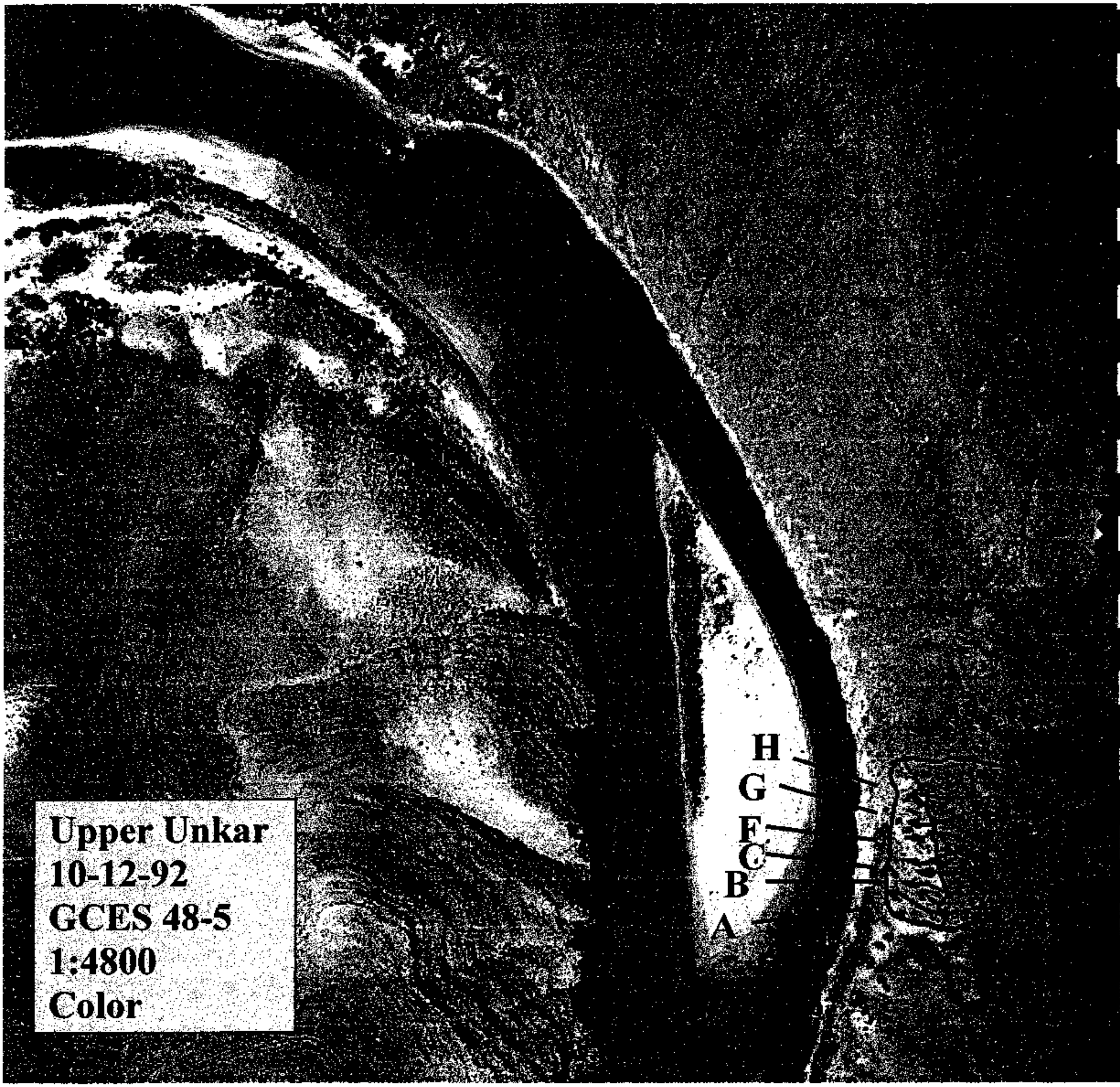

Comanche Creek Area L
10-12-92
GCES 45-11
Color
1:4800


B
A
Tanner Creek
4-6-96
GCES 47-4
B&W
1:4800

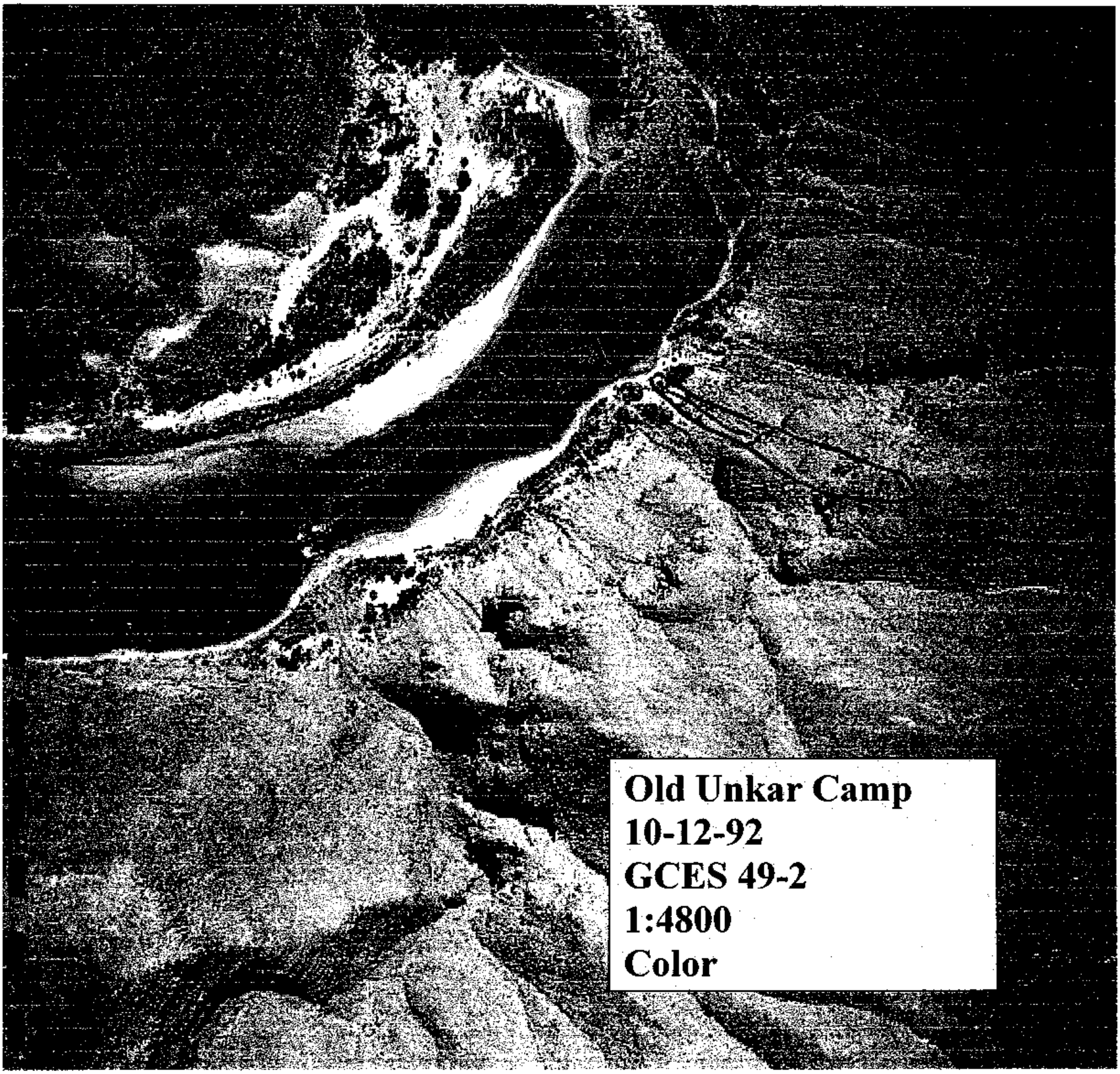

Basalt Canyon
4-6-96
GCES 46-6
B&W
1:4800
A
B
C

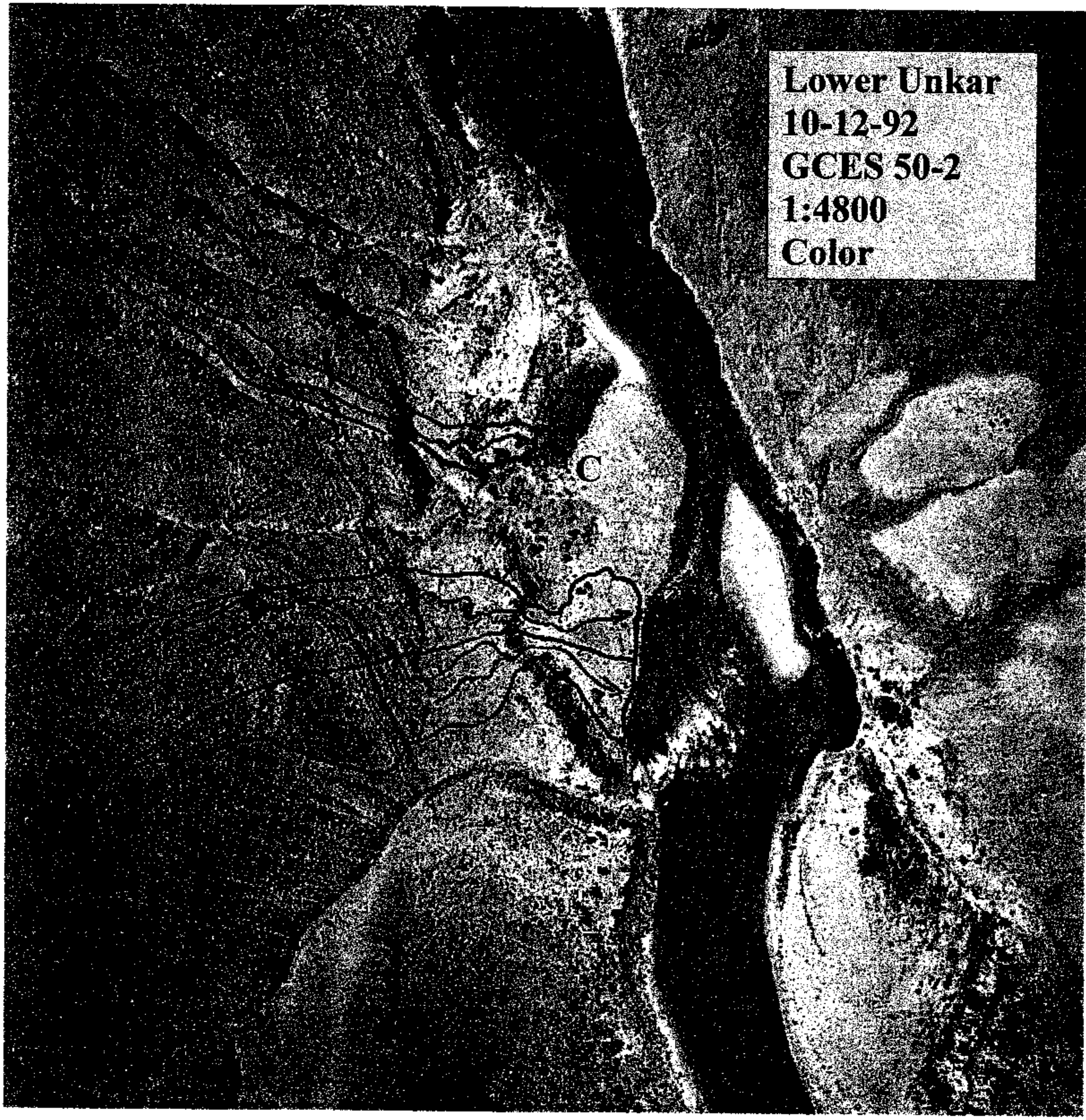

C
B
A
Lower Tanner Area
4-6-96
GCES 47-4
B&W
1:4800


Lower Tanner Area
4-6-96
GCES 47-3
B&W
1:4800
F
E
D

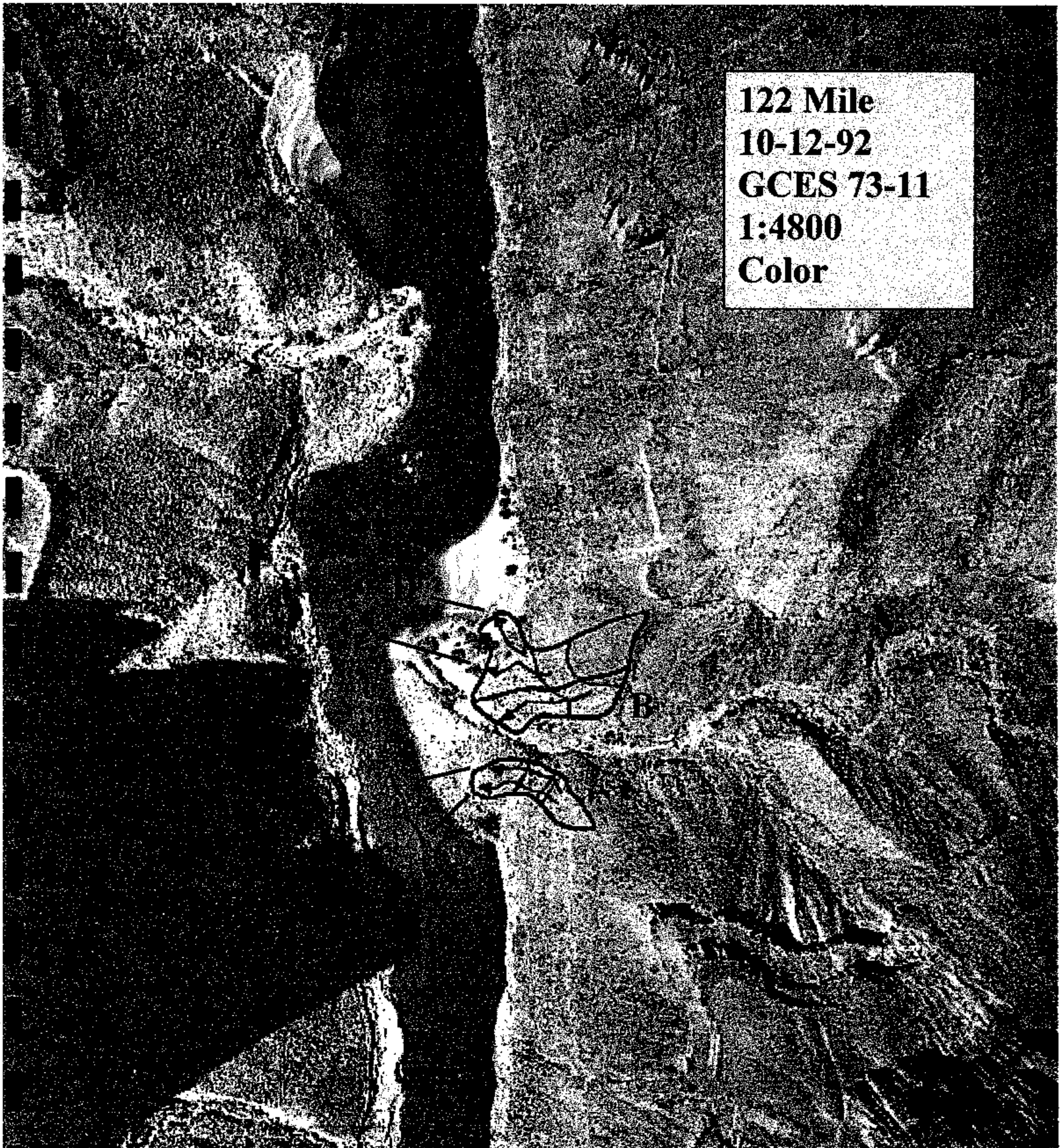


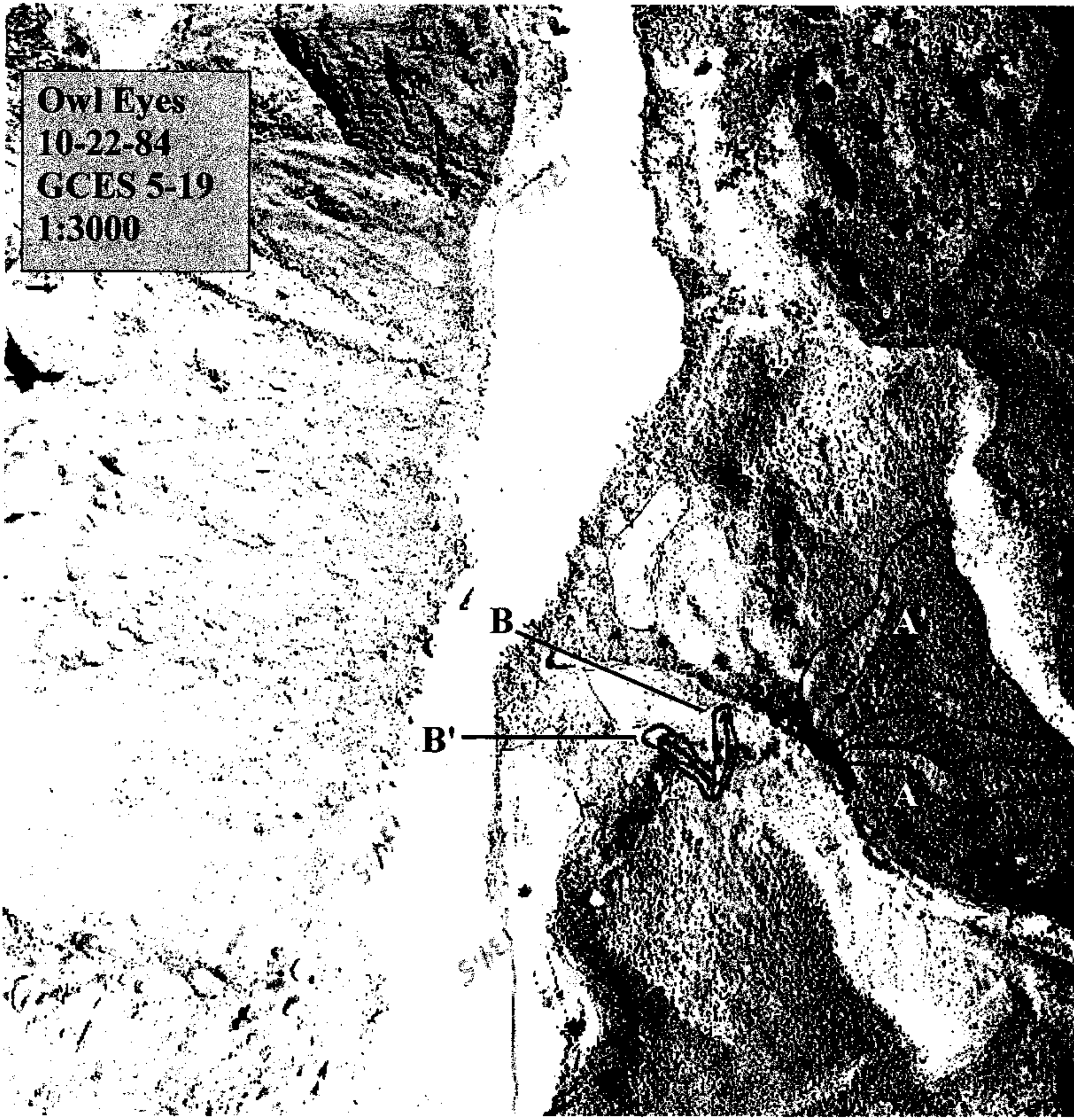
Upper Unkar
10-12-92
GCES 48-5
1:4800
Color
H
G
F
C
B
A

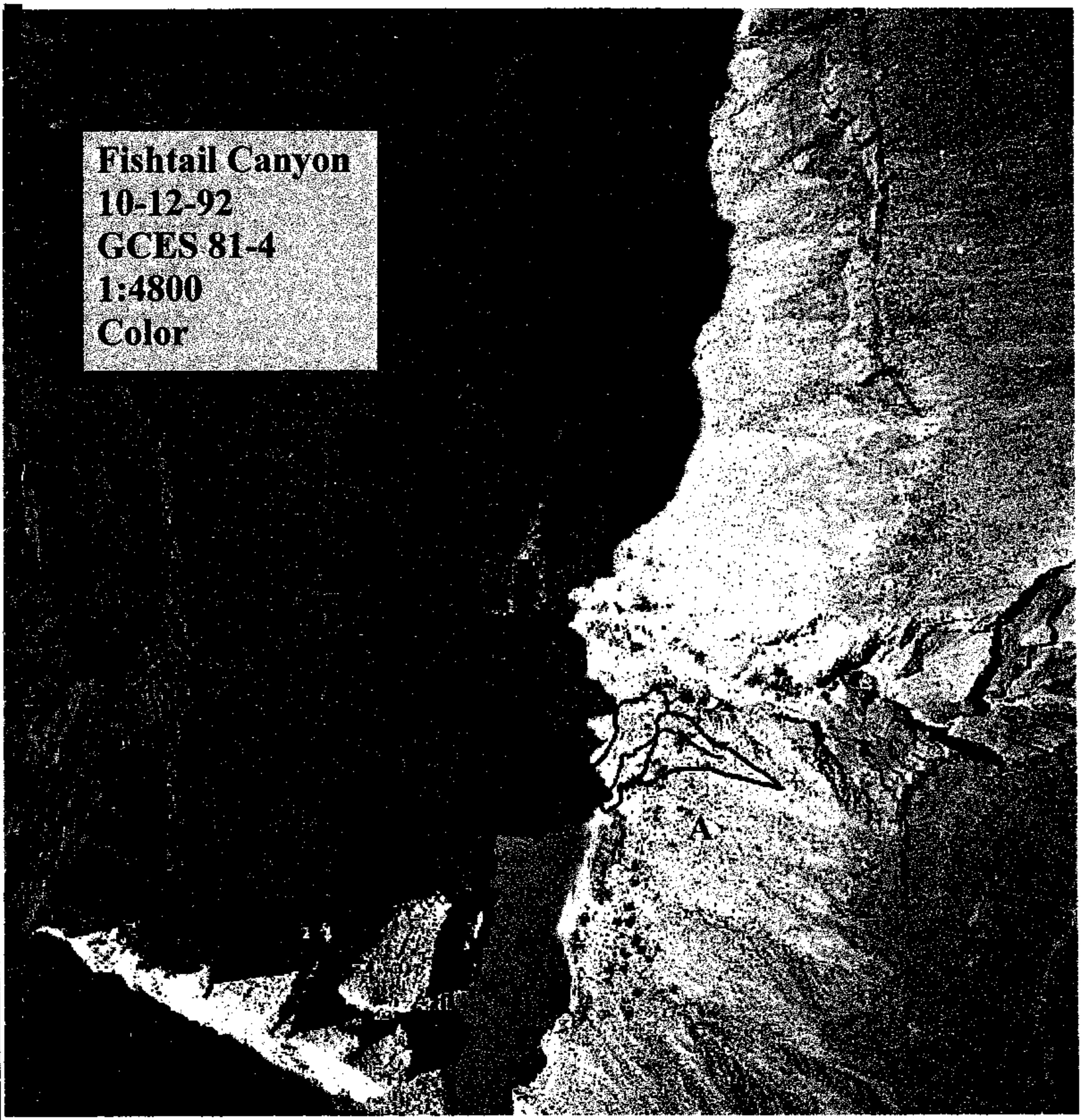

Old Unkar Camp
10-12-92
GCES 49-2
1:4800
Color

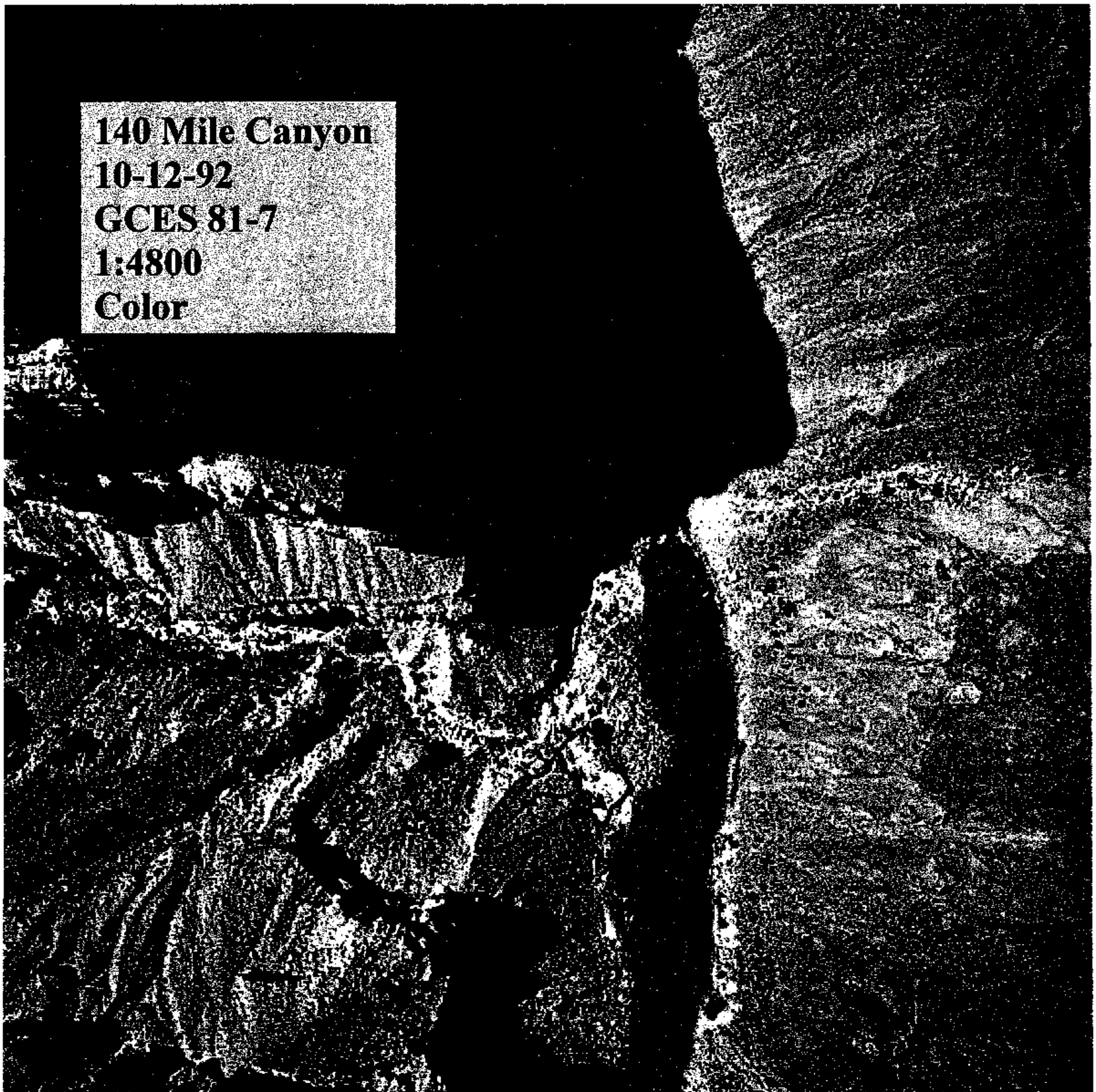


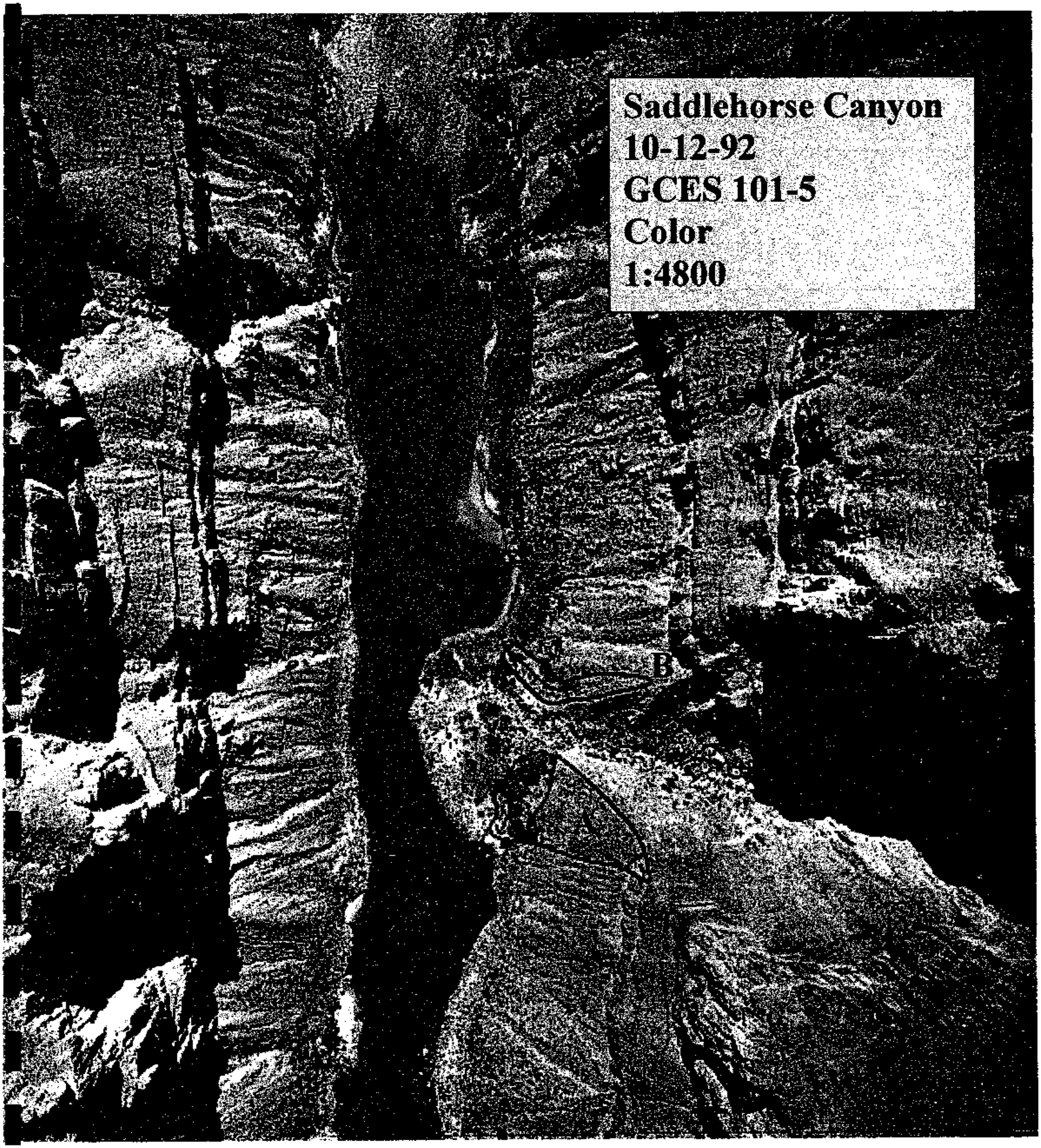
Lower Unkar
10-12-92
GCES 50-2
1:4800
Color
C


122 Mile
10-12-92
GCES 73-11
1:4800
Color
B

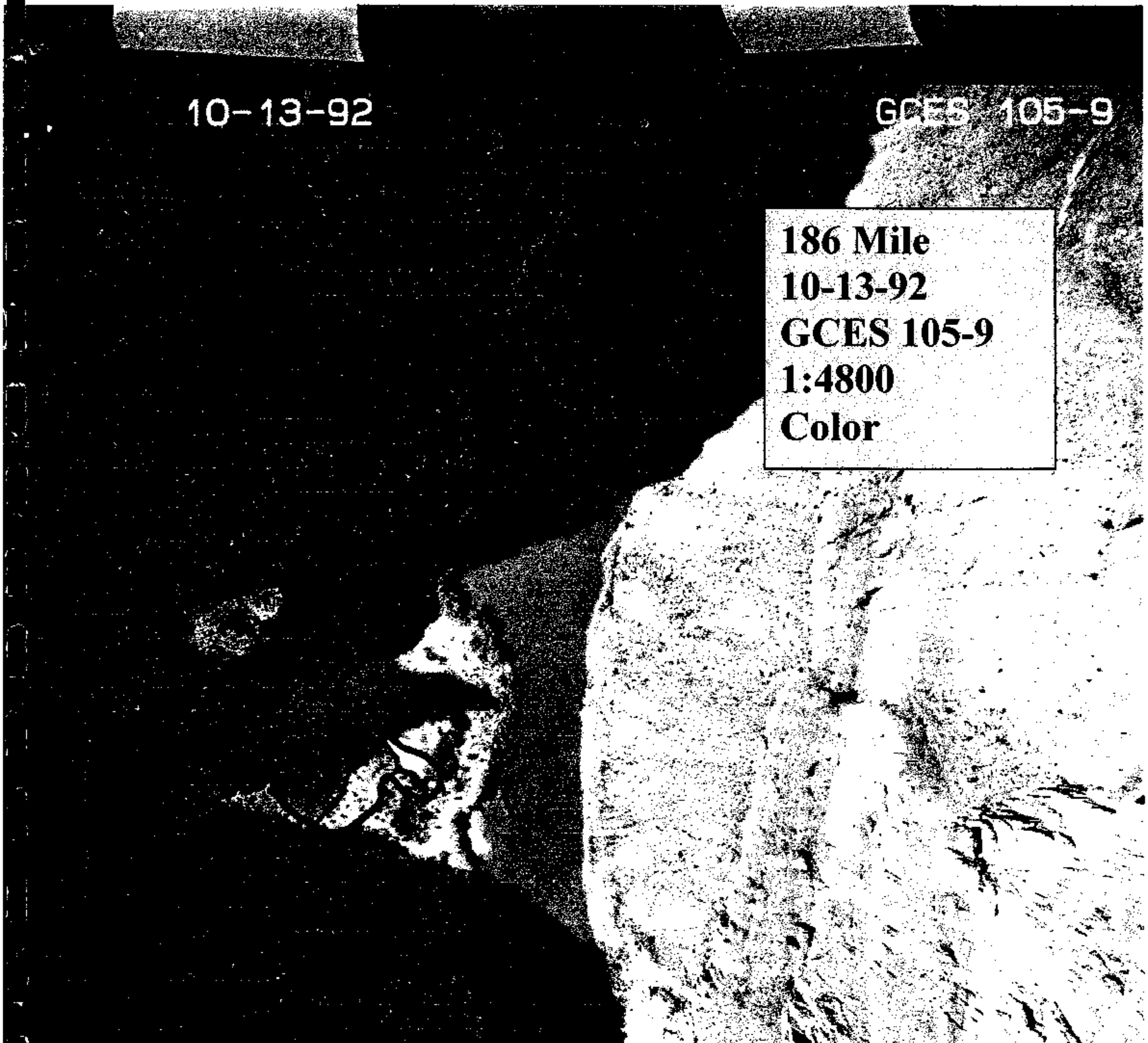

Owl Eyes
10-22-84
GCES 5-19
1:3000
B
B'
A'
A

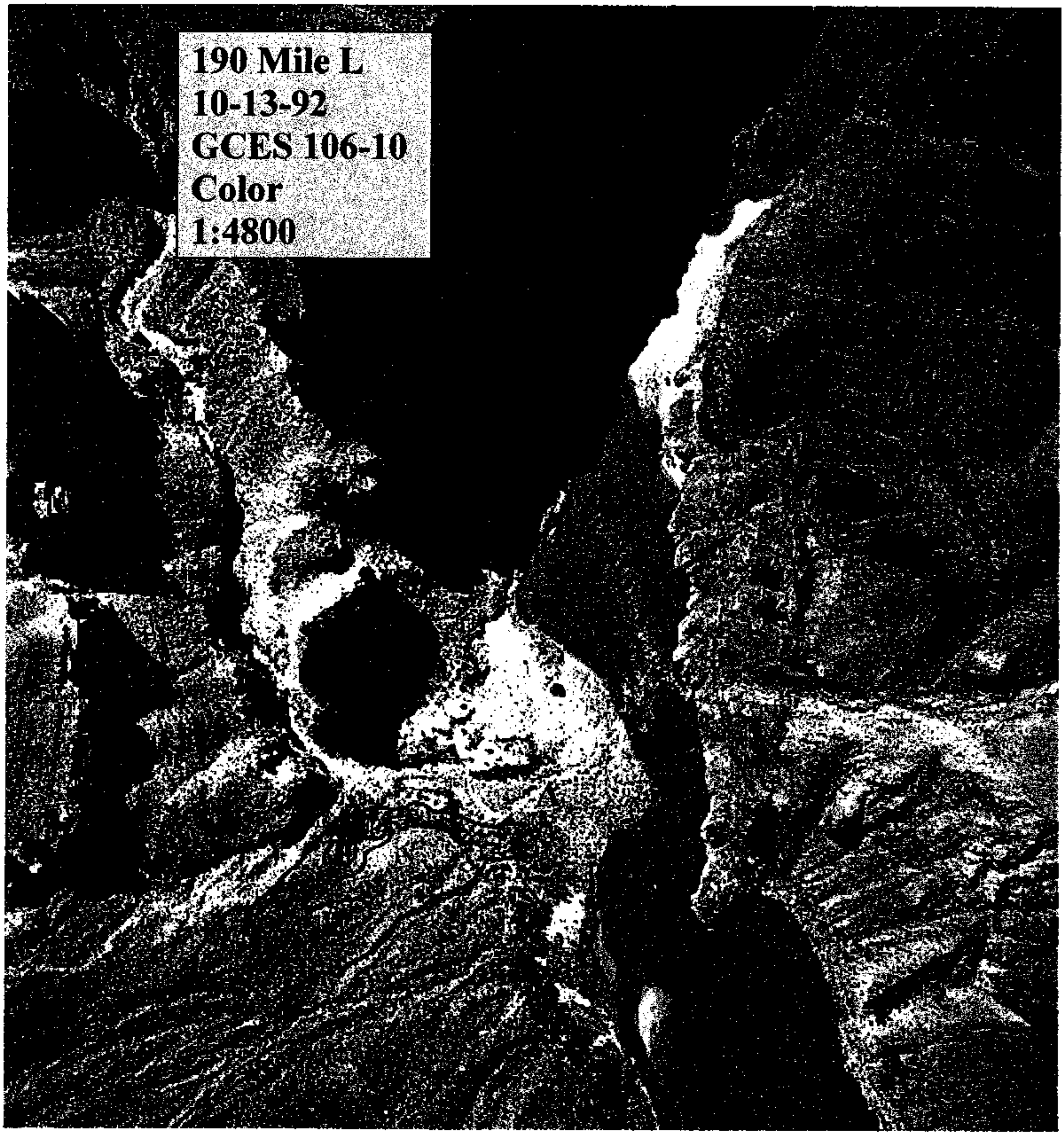

Fishtail Canyon
10-12-92
GCES 81-4
1:4800
Color
A

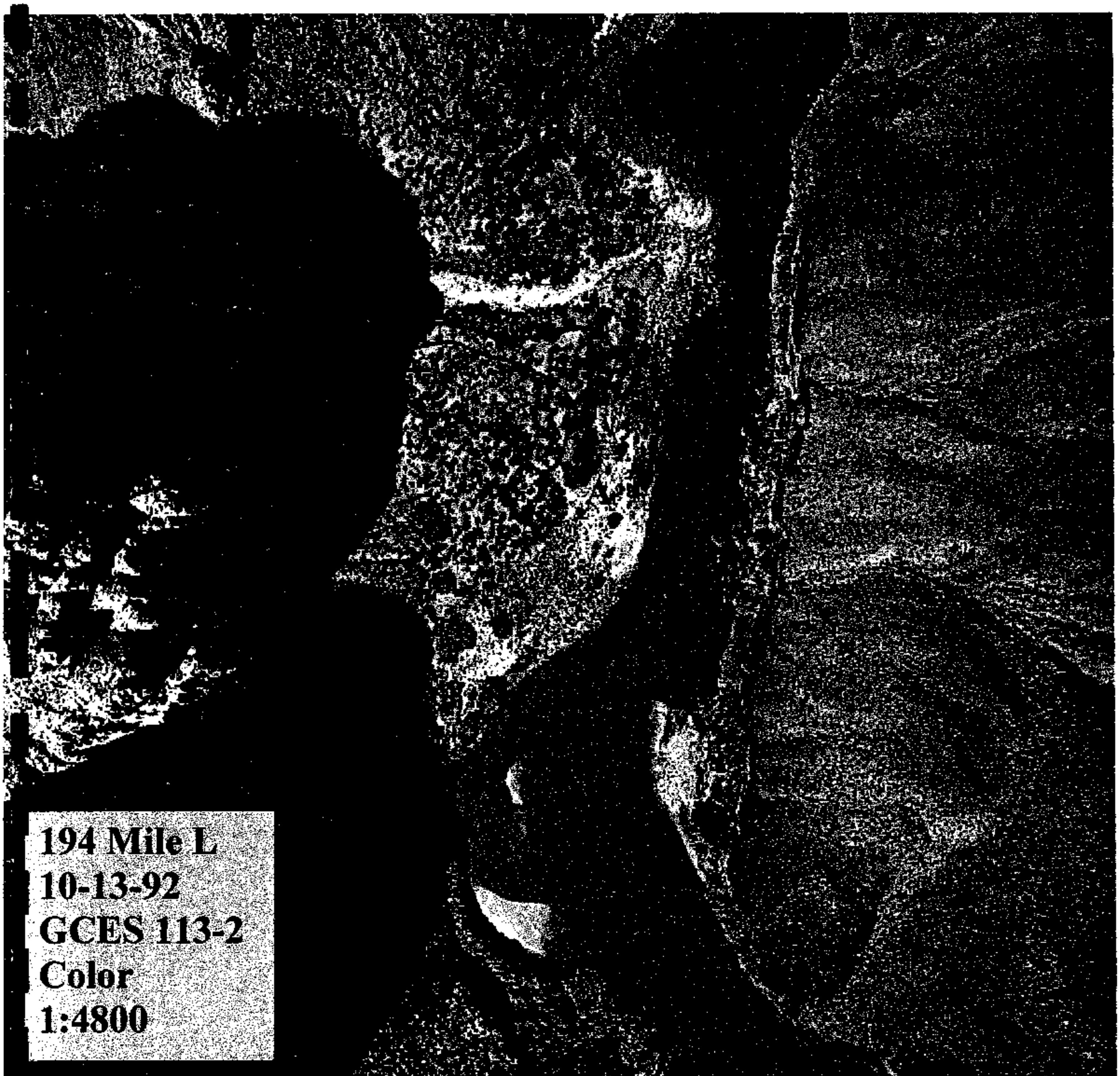

140 Mile Canyon
10-12-92
GCES 81-7
1:4800
Color

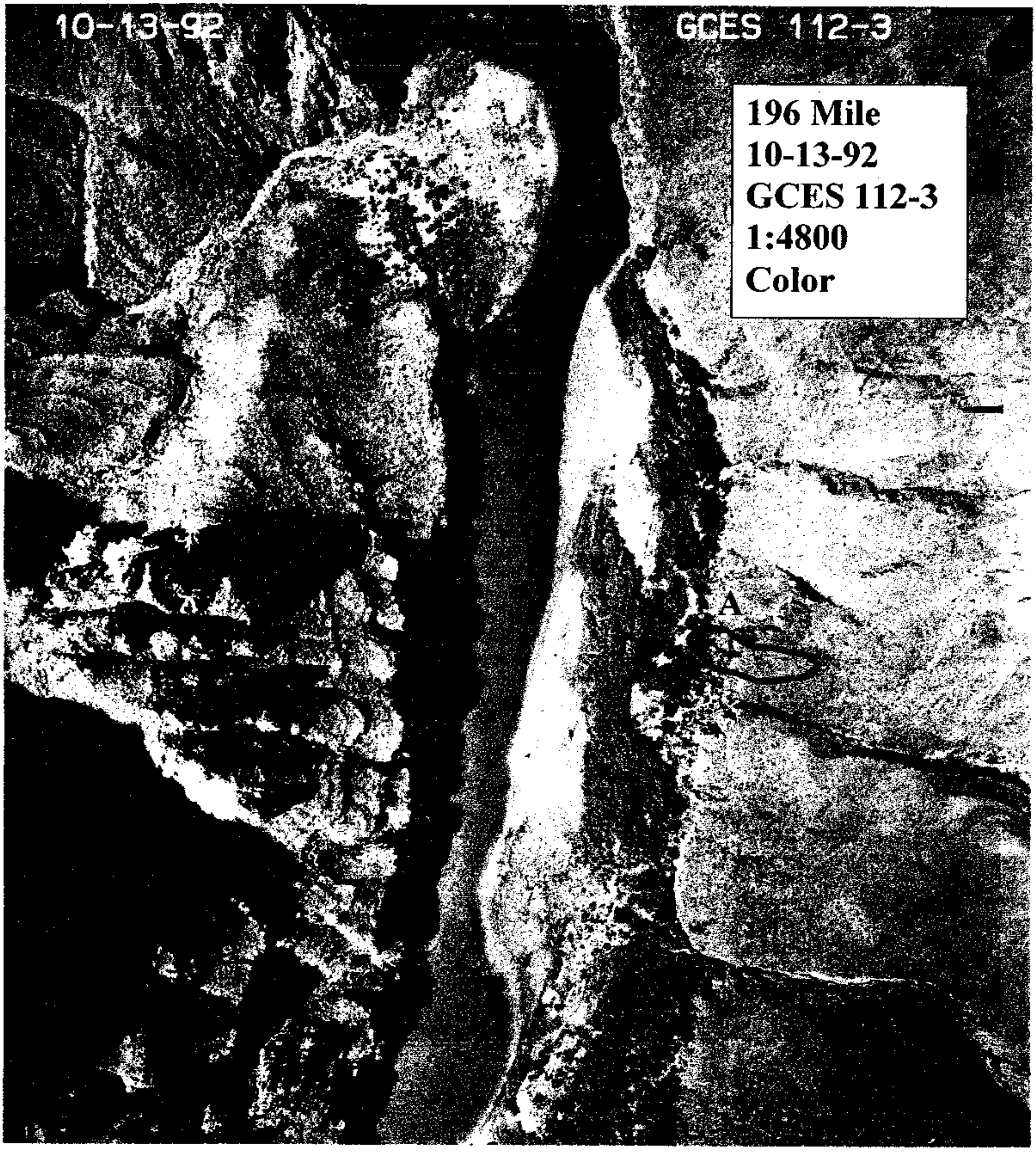

Saddlehorse Canyon
10-12-92
GCES 101-5
Color
1:4800
B

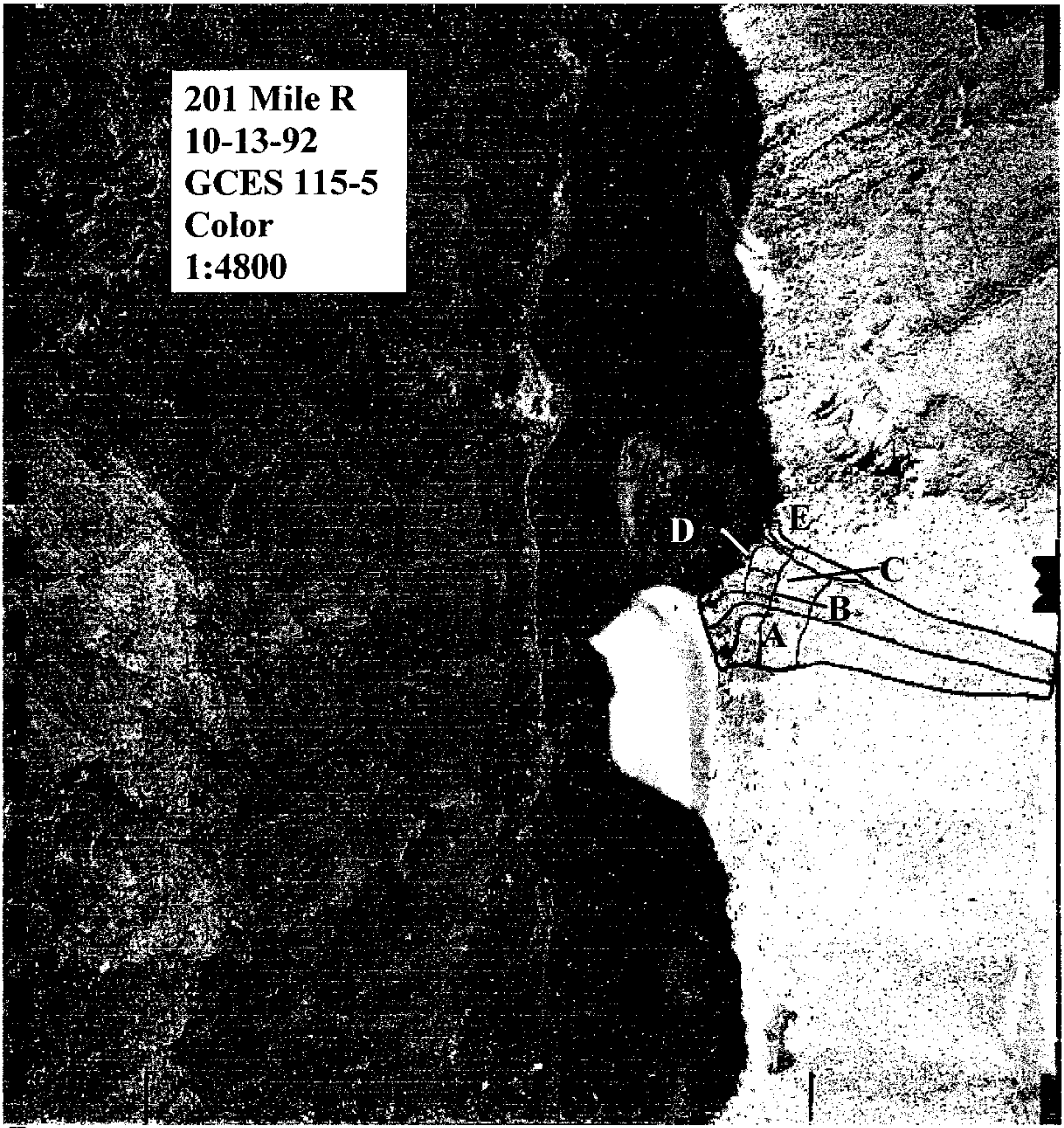
Old Heli Pad(183 Mile)
10-13-92
GCES 103-10
1:4800
Color
A

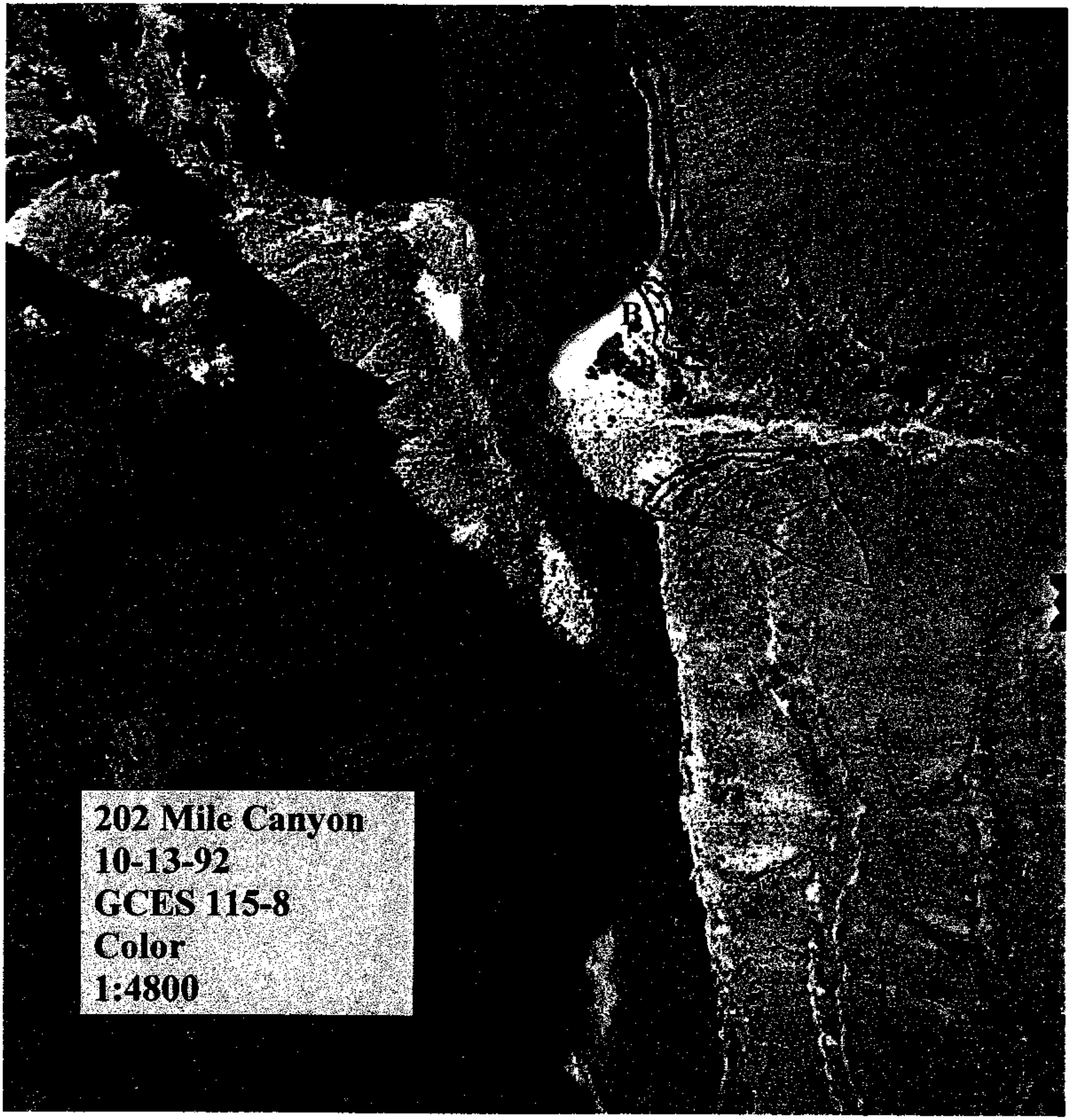

10-13-92
GCES 105-9
186 Mile
10-13-92
GCES 105-9
1:4800
Color

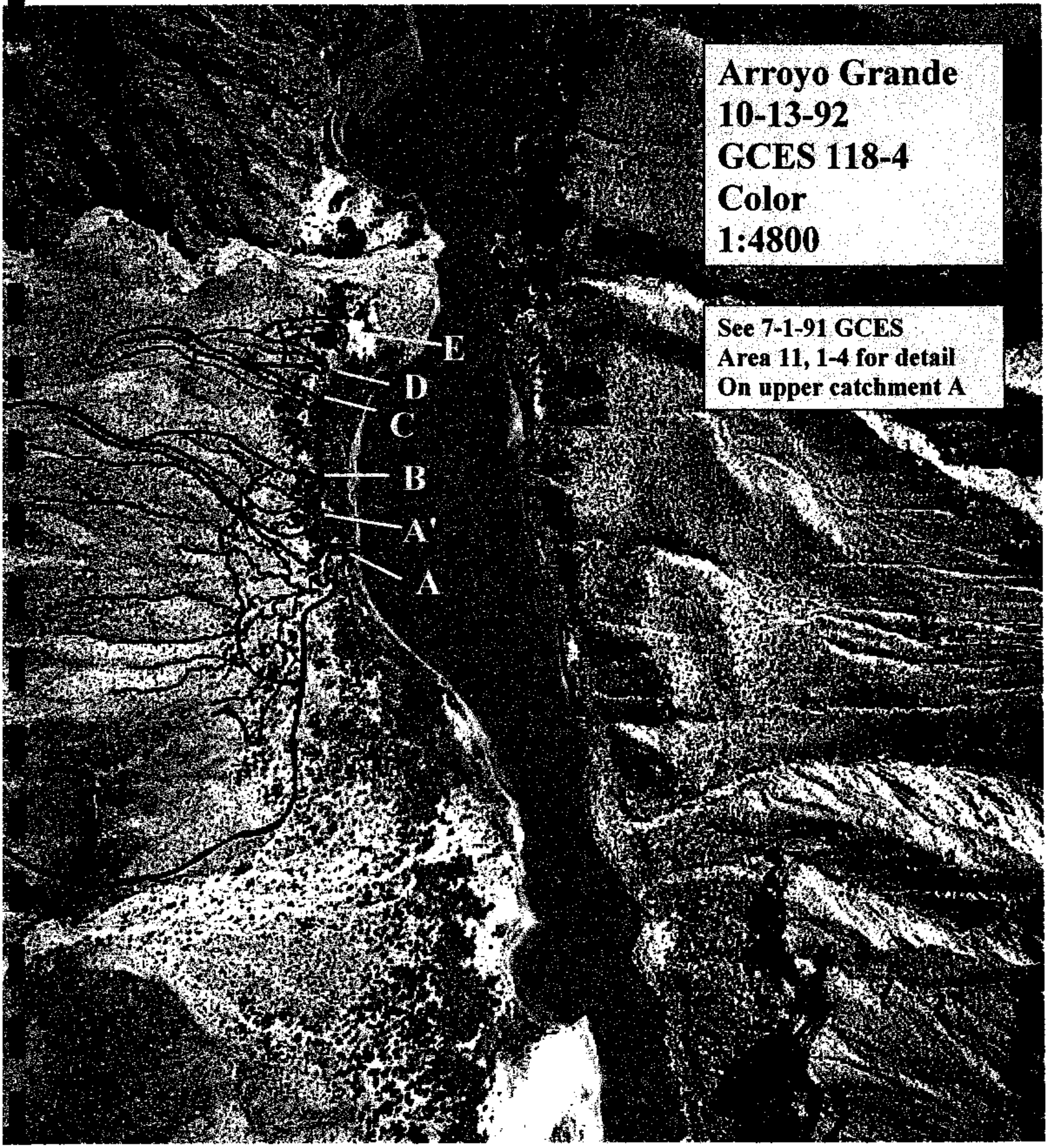

190 Mile L
10-13-92
GCES 106-10
Color
1:4800

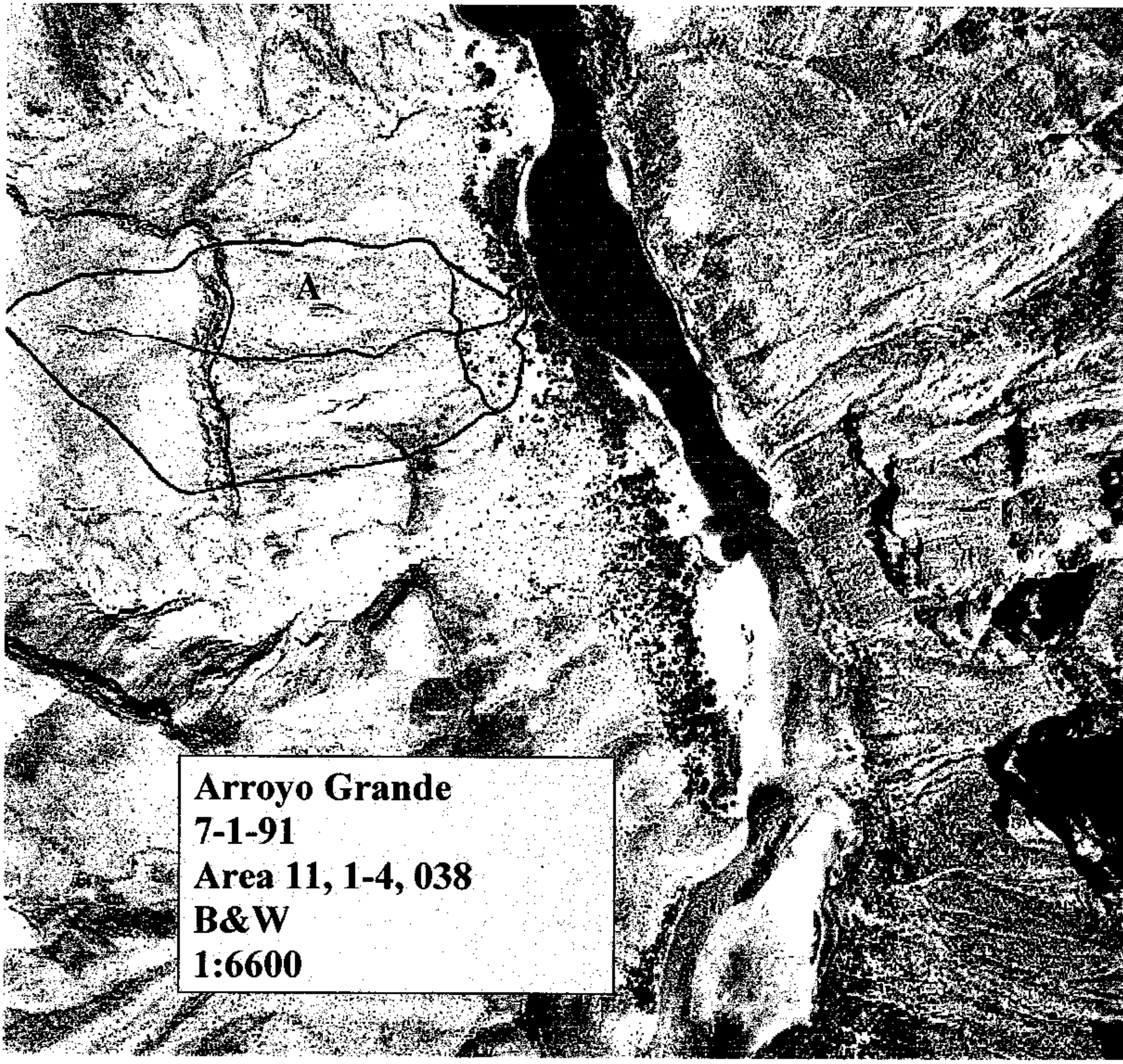

194 Mile L
10-13-92
GCES 113-2
Color
1:4800

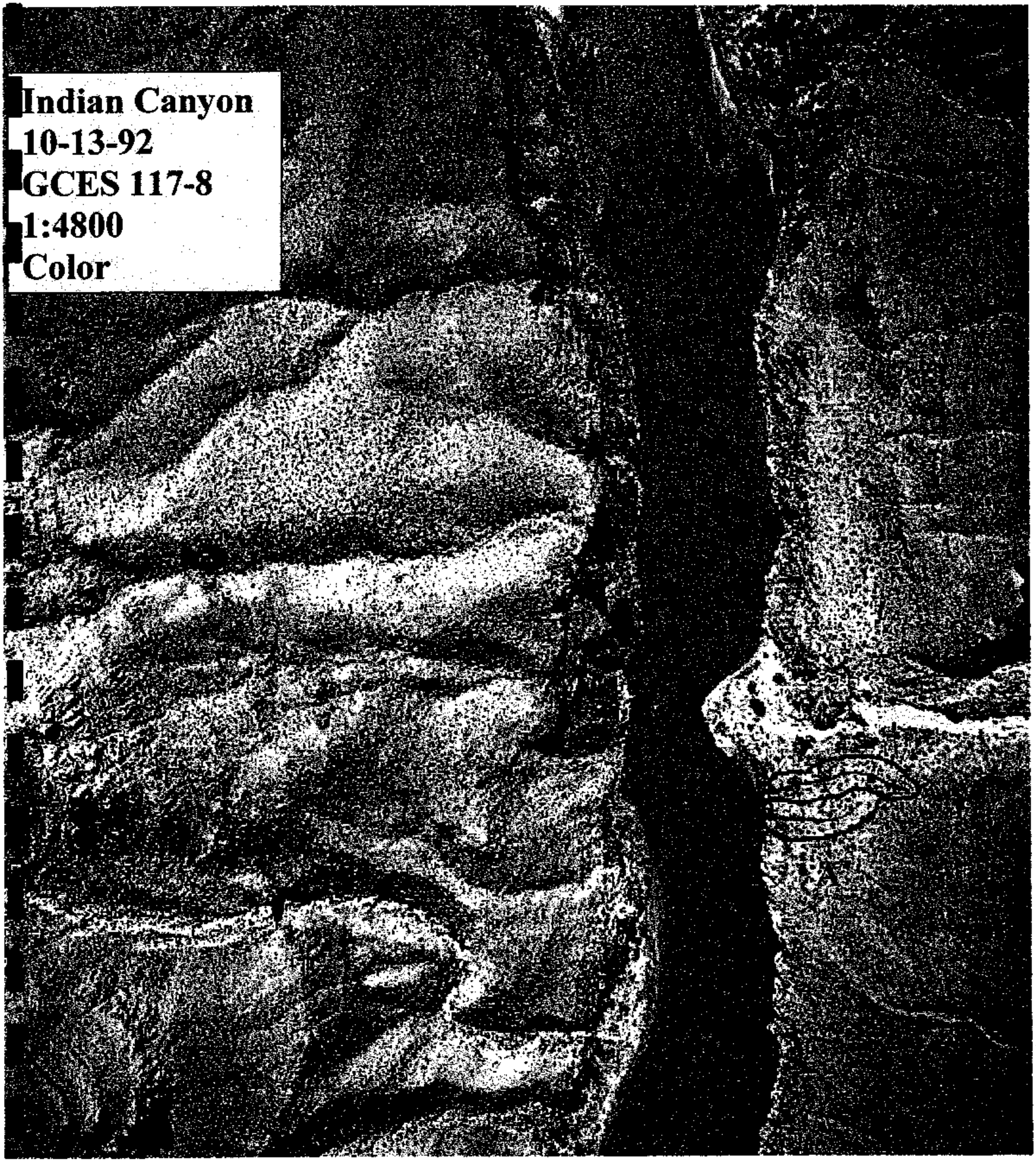

10-13-92
GCES 112-3
196 Mile
10-13-92
GCES 112-3
1:4800
Color
A

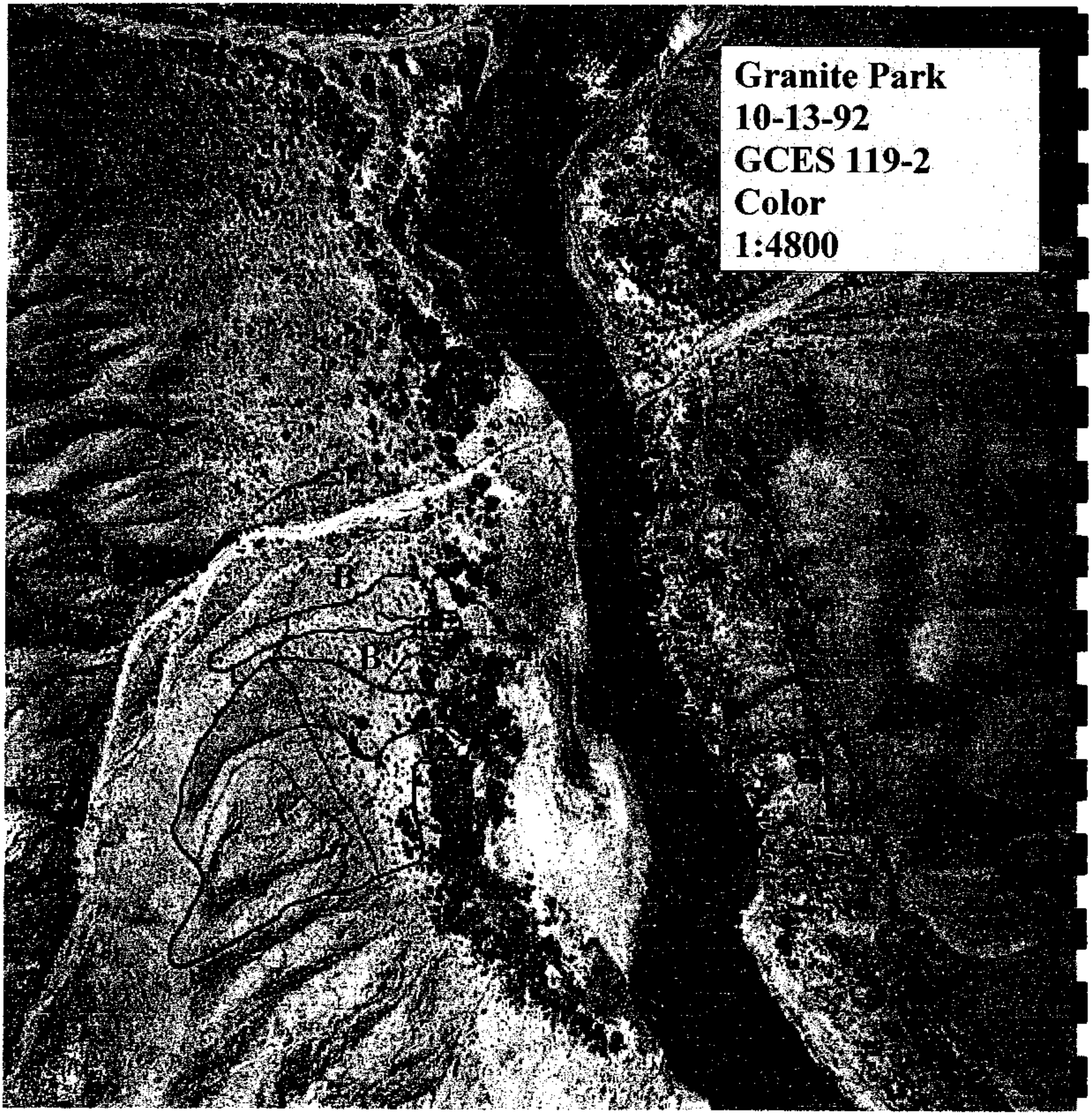

201 Mile R
10-13-92
GCES 115-5
Color
1:4800
D
E
C
B
A

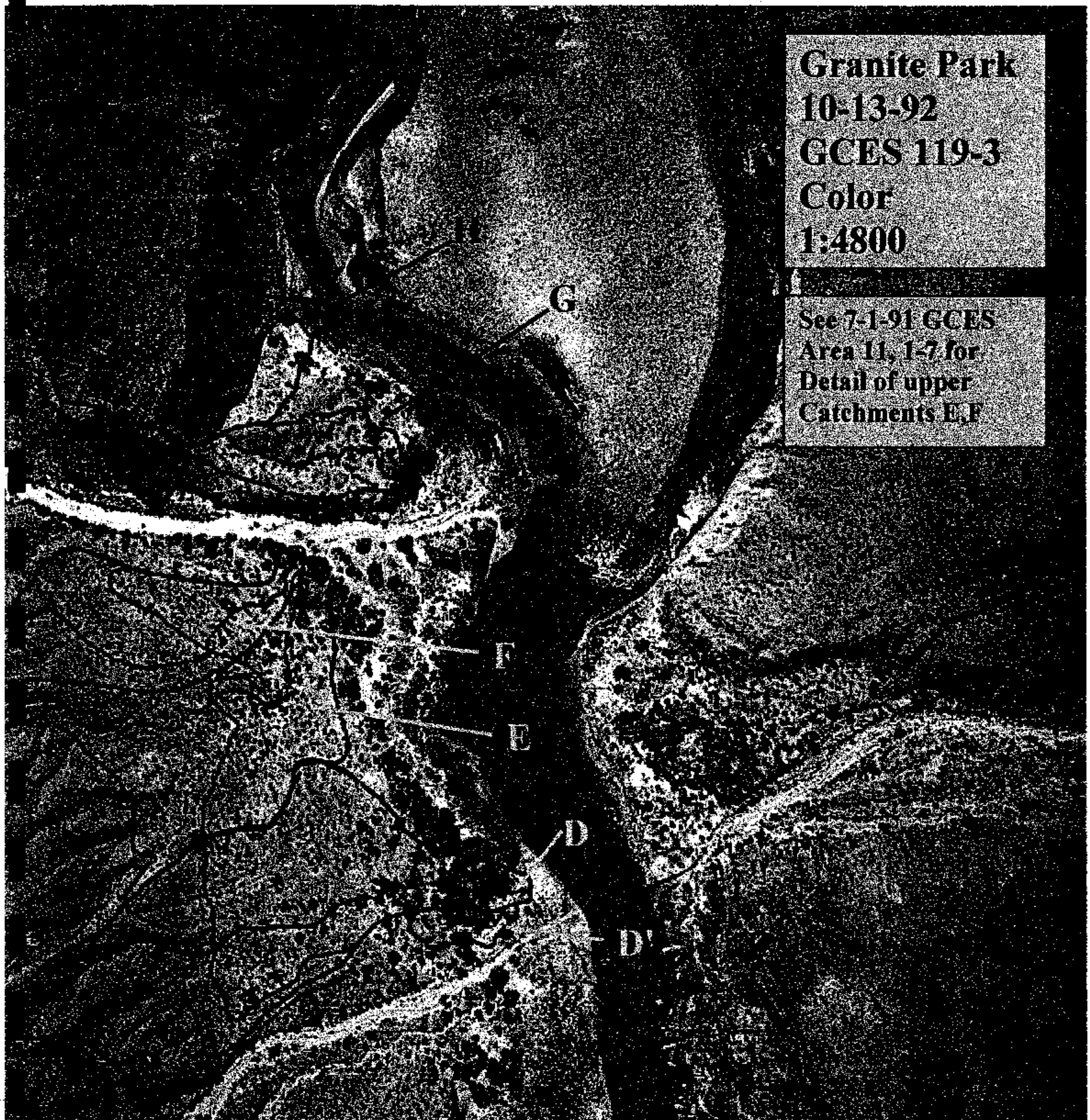

B
202 Mile Canyon
10-13-92
GCES 115-8
Color
1:4800

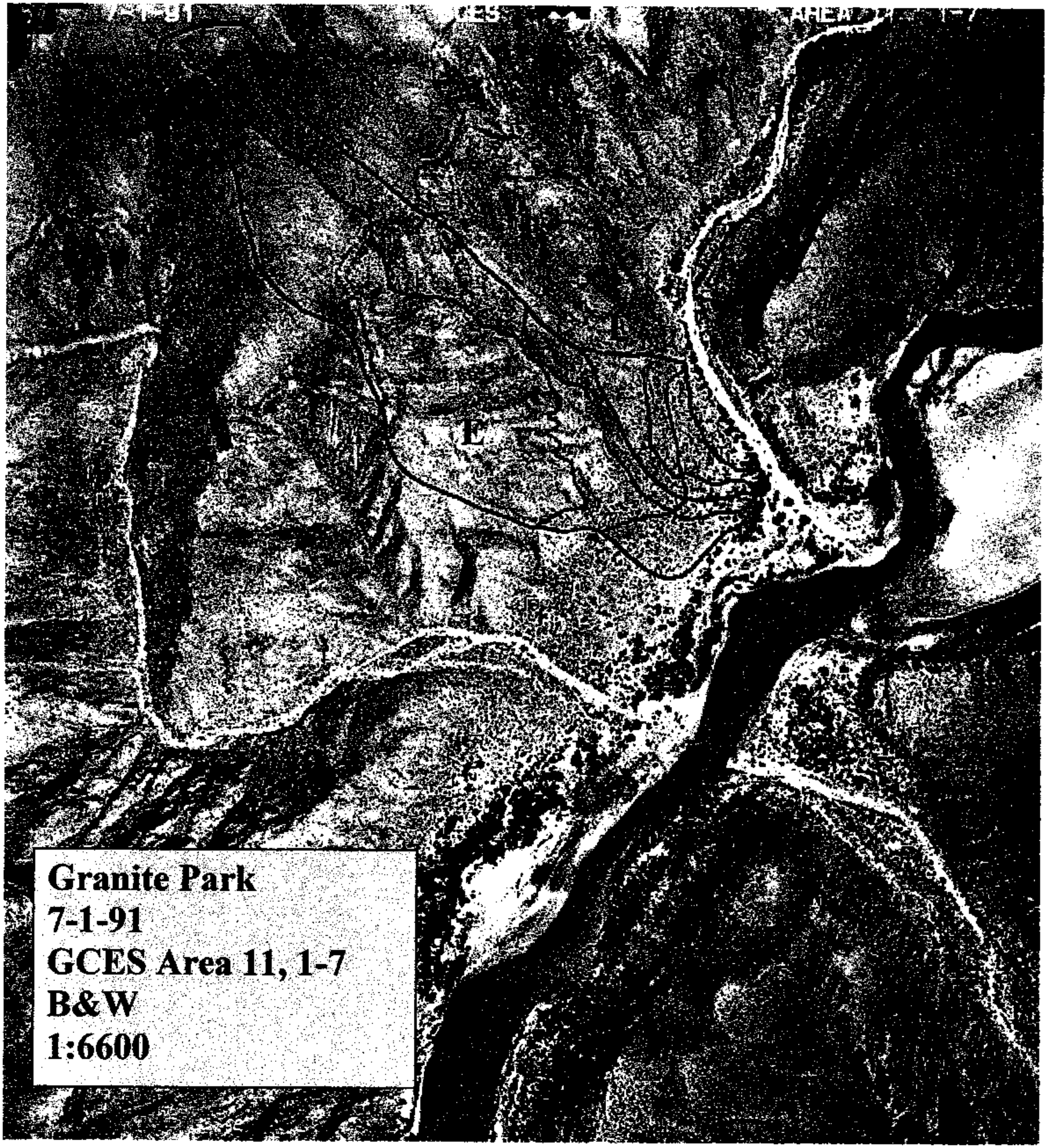

Arroyo Grande
10-13-92
GCES 118-4
Color
1:4800
See 7-1-91 GCES
Area 11, 1-4 for detail
On upper catchment A
E
D
C
B
A'
A


A
Arroyo Grande
7-1-91
Area 11, 1-4, 038
B&W
1:6600

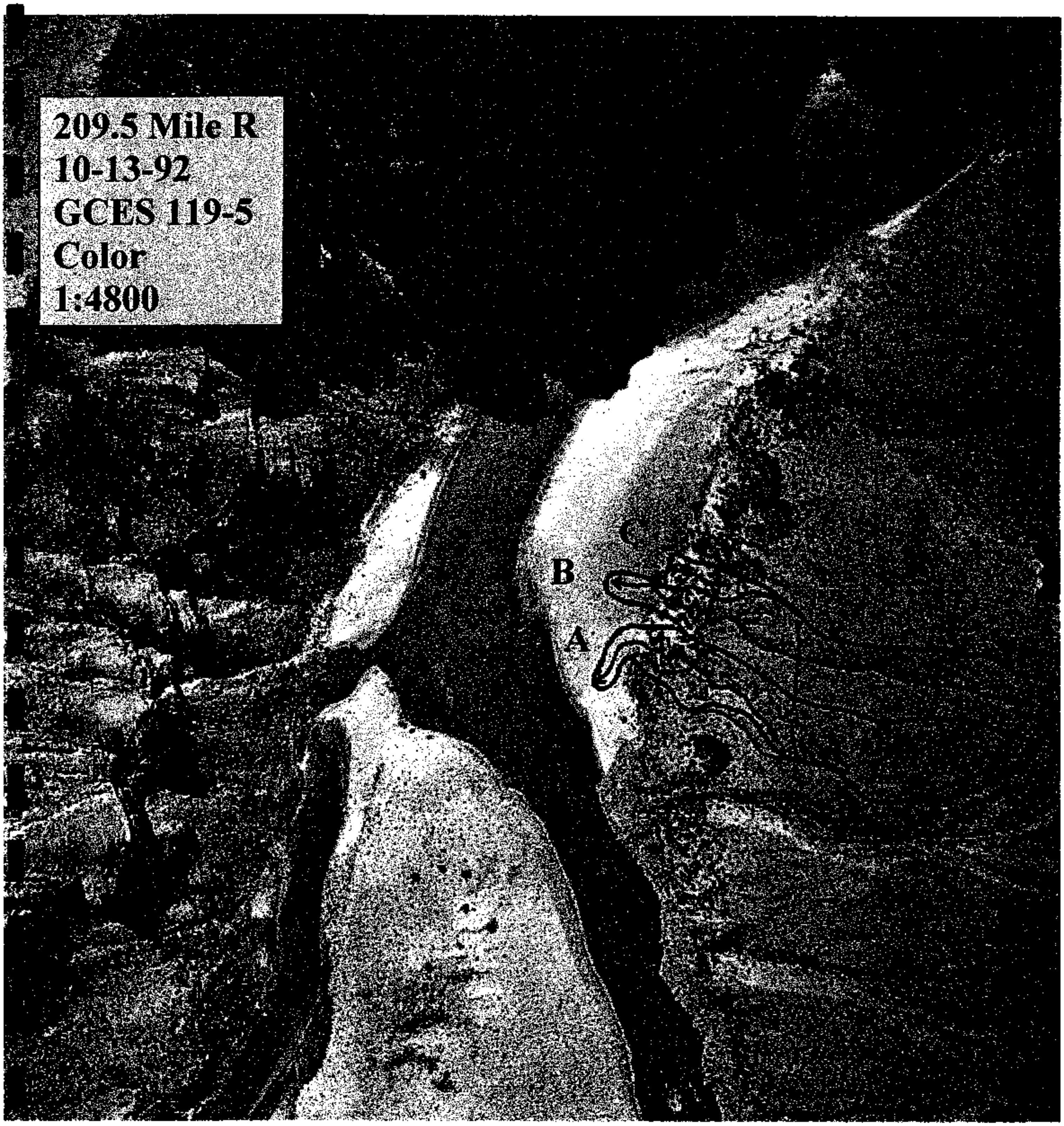

Indian Canyon
10-13-92
GCES 117-8
1:4800
Color

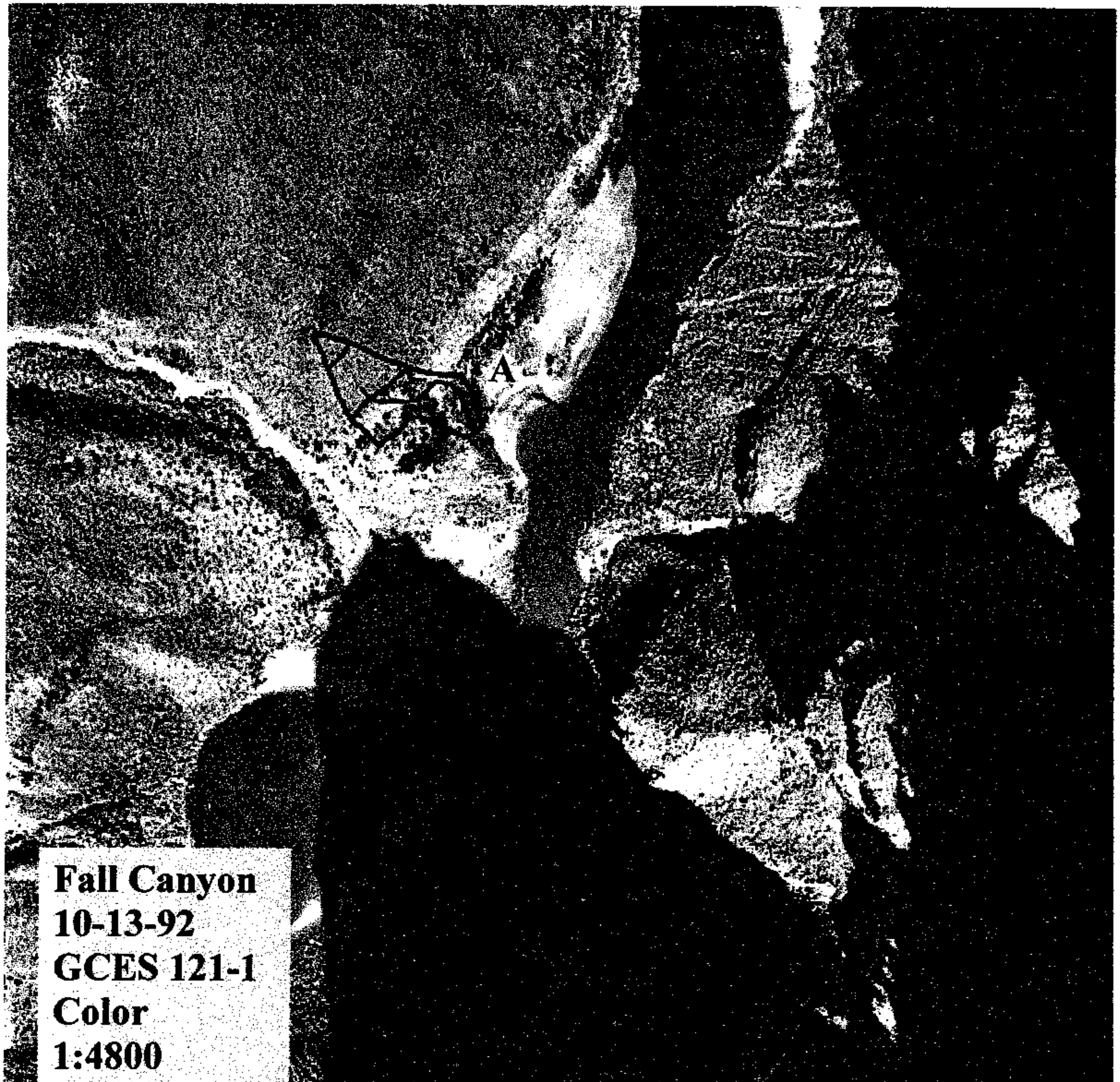

Granite Park
10-13-92
GCES 119-2
Color
1:4800
B
B


Granite Park
10-13-92
GCES 119-3
Color
1:4800
See 7-1-91 GCES
Area 11, 1-7 for
Detail of upper
Catchments E,F
H
G
F
E
D
D'



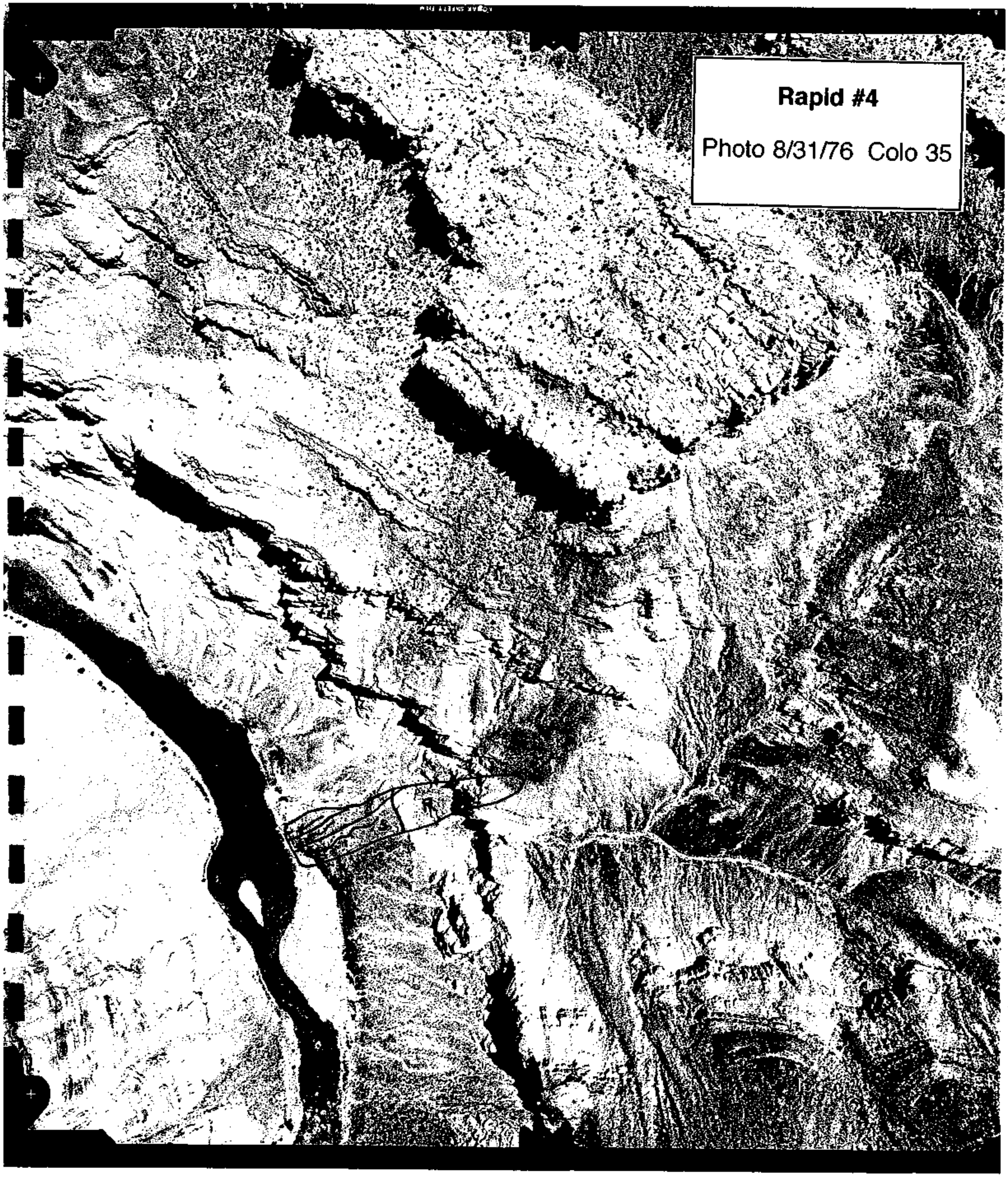
Granite Park
7-1-91
GCES Area 11, 1-7
B&W
1:6600


209.5 Mile R
10-13-92
GCES 119-5
Color
1:4800
B
A


A
Fall Canyon
10-13-92
GCES 121-1
Color
1:4800

APPENDIX E

AIR PHOTOS OF CATARACT CANYON CATCHMENT AREAS


Rapid #4
Photo 8/31/76 Colo 35

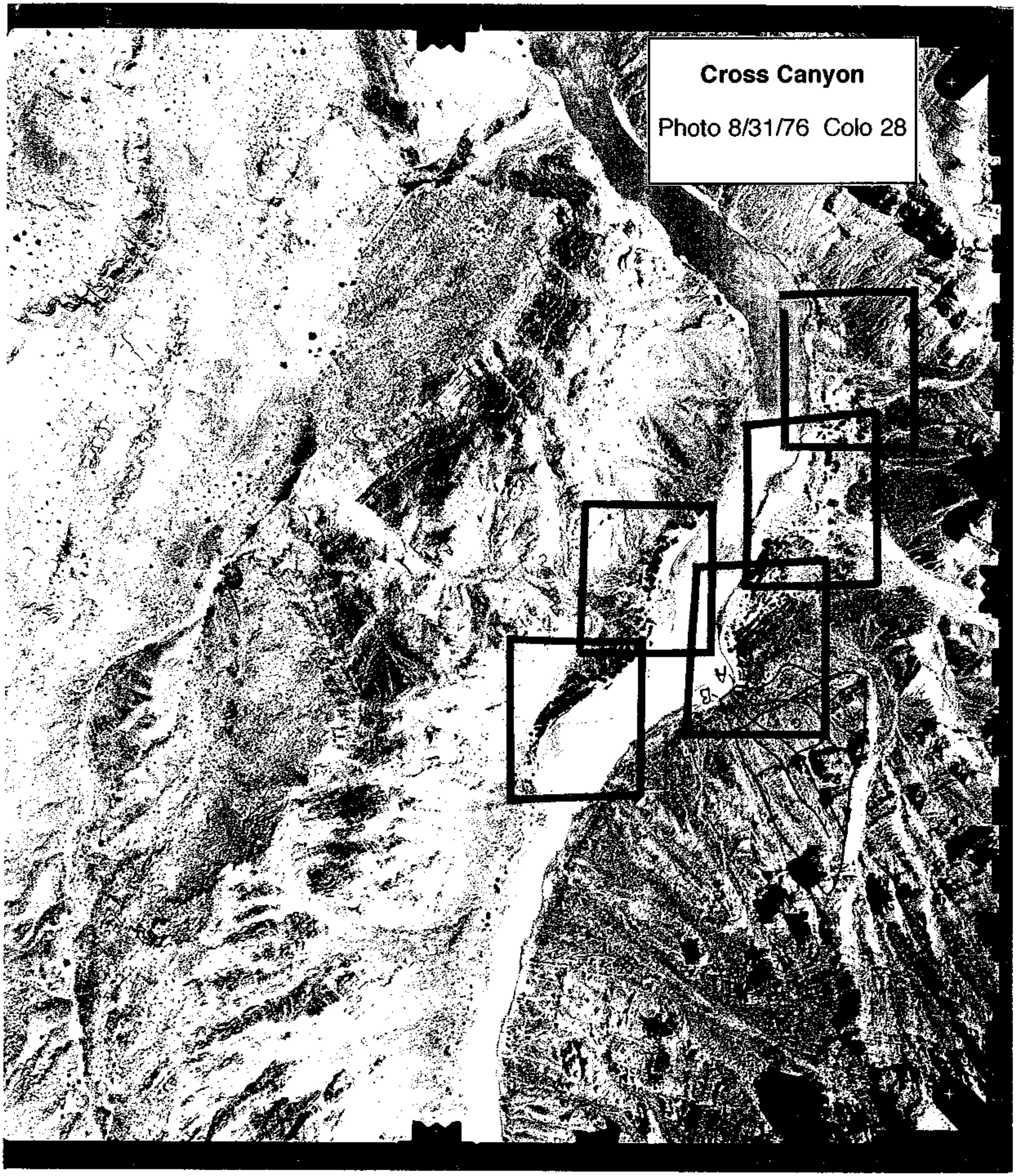

Cross Canyon

Photo 8/31/76 Colo 28


Rapid #12
Photo 8/31/76 Colo 23

Plate 1. Key

Location where drainiage cross section was measured
(actual plots and measurements available in ArcView and Excel datafiles)

Thalweg

Catchment area

Cultural area

Eolian deposit

Stream alluvium

High-flow sand deposit of <45,000 cfs (1984-86, 1996)

Flood-flow sand deposit of <97,000 cfs (1983)

Pre-dam alluvial sand of 108,000-125,000 cfs (1922-1958)

Lower mesquite terrace sand of 220,000-300,000 cfs (1884-1921)

Upper mesquite terrace sand of 300,000-500,000 cfs (1400-1883)

Playa deposit: ponded alluvial fine sediment at Palisades Creek

Alluvium of puebloan age, terrace sand of >500,000 cfs (A.D.700-1200)

Striped alluvium terrace sand of >500,000 cfs (before 770 B.C.- A.D.300)

River gravel

Debris fan: deltaic, unchannelized debris flow deposits of gravel at mouths of large tributary canyons

Debris fan: lobe, unchannelized and channelized debris flow deposits of gravel at channel mouths of small to medium sized tributary canyons

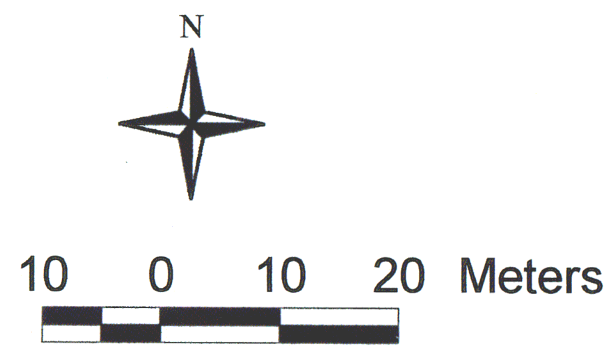
Alluvial fan: fine gravel distributary deposits at the mouths of small tributary canyons

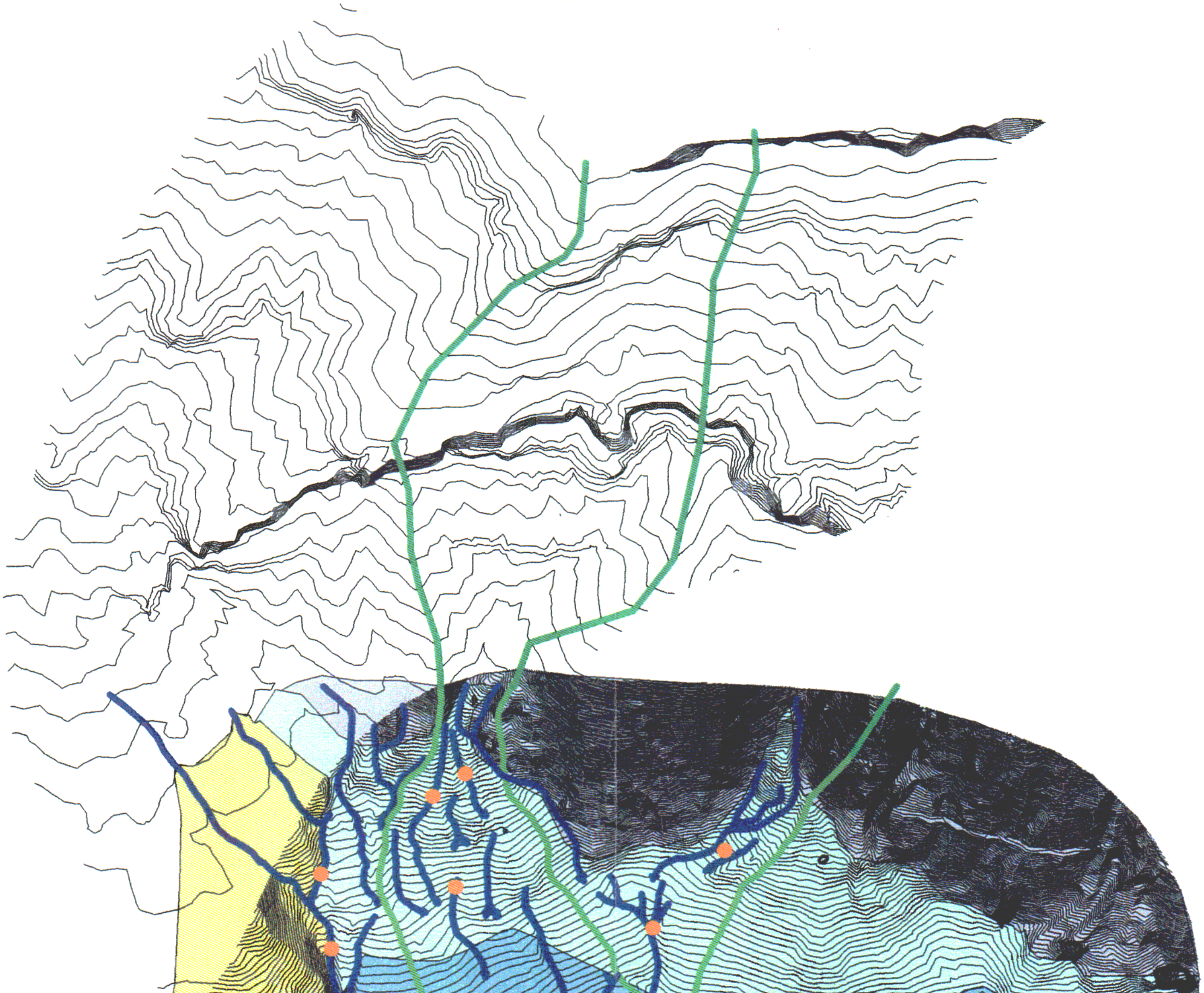
Talus: colluvium at base of bedrock cliffs

Bedrock

Plate 2. NANKOWEAP ALLUVIAL FAN GEOMORPHIC SETTING

- Location where drainage cross section was measured (actual plots and measurements available in ArcView and Excel datafiles)
- Cultural area
- Thalweg
- Catchment area
- Eolian deposit
- High-flow sand deposit
- Flood-flow sand deposit
- Pre-dam alluvium
- Lower mesquite terrace
- Upper mesquite terrace
- Alluvium of puebloan age
- Striped alluvium
- Debris fan-lobe
- Alluvial fan
- Talus
- Bedrock-Cambrian Tonto Group




COLORADO RIVER

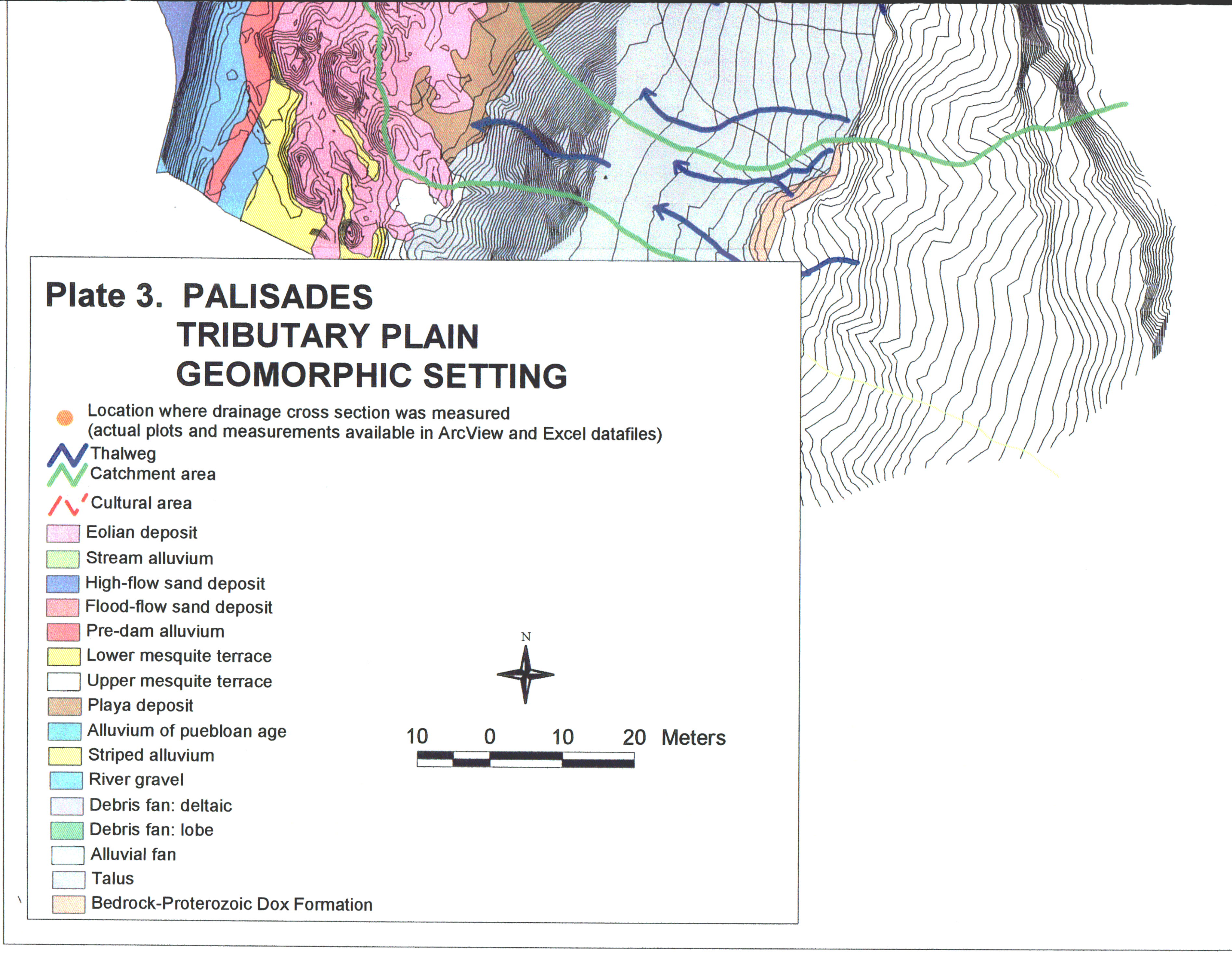
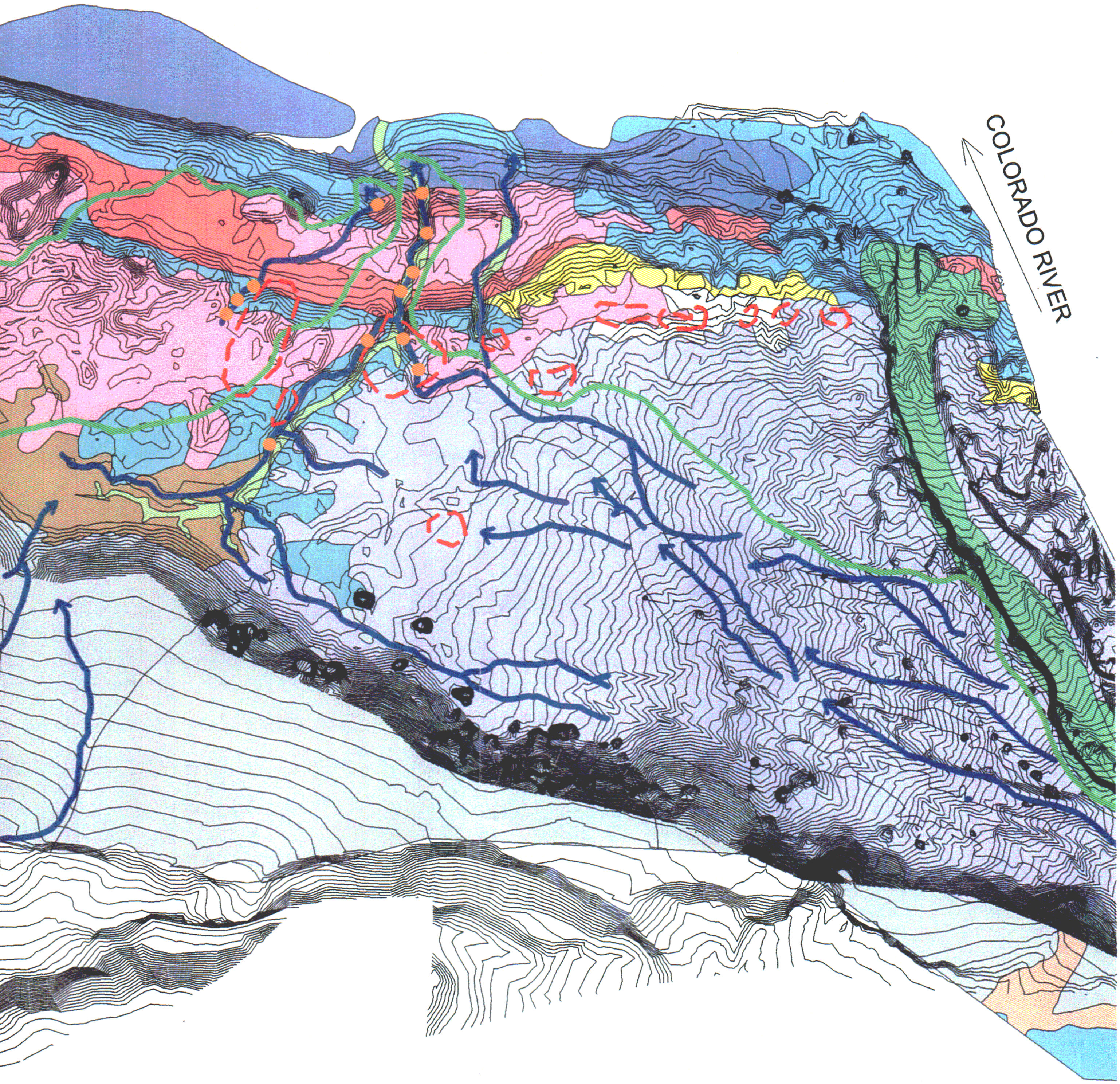


Plate 3. PALISADES
TRIBUTARY PLAIN
GEOMORPHIC SETTING
Location where drainage cross section was measured
(actual plots and measurements available in ArcView and Excel datafiles)
Thalweg
Catchment area
Cultural area
Eolian deposit
Stream alluvium
High-flow sand deposit
Flood-flow sand deposit
Pre-dam alluvium
Lower mesquite terrace
Upper mesquite terrace
Playa deposit
Alluvium of puebloan age
Striped alluvium
River gravel
Debris fan: deltaic
Debris fan: lobe
Alluvial fan
Talus
Bedrock-Proterozoic Dox Formation
N
10 0 10 20 Meters


COLORADO RIVER

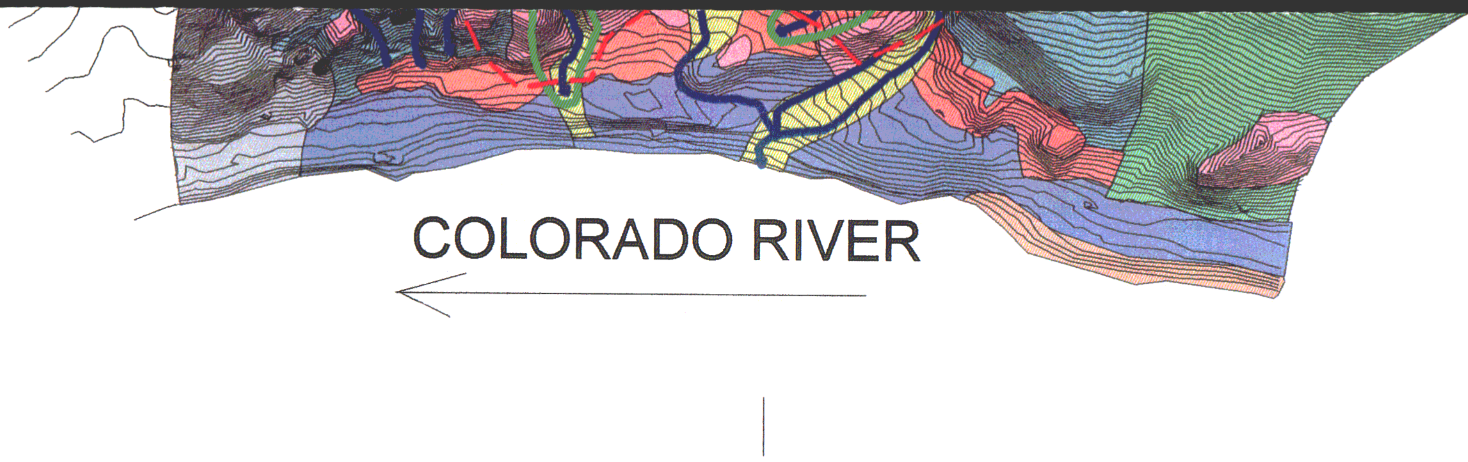
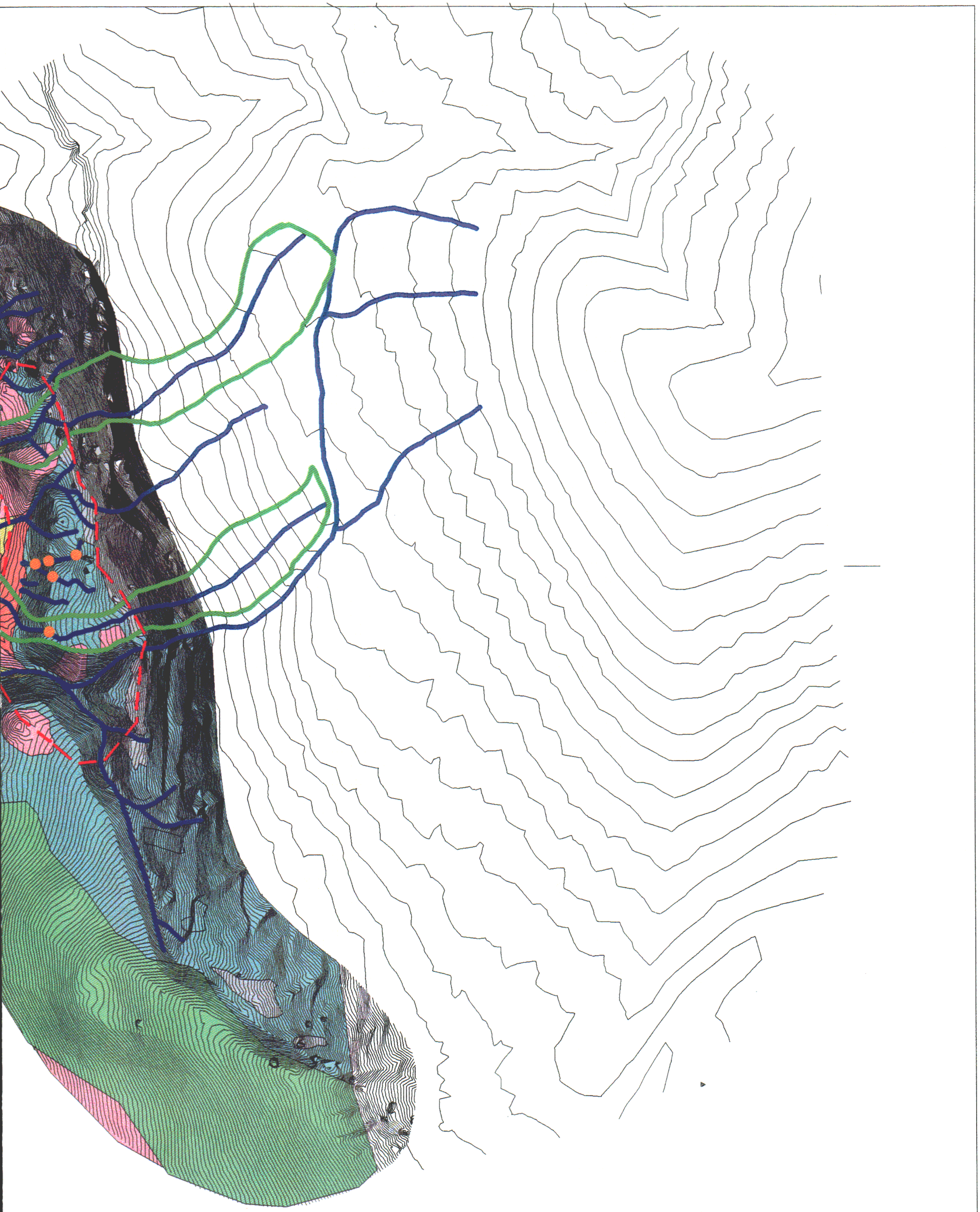


Plate 4. UPPER UNKAR OR FURNACE FLATS TALUS SLOPE GEOMORPHIC SETTING

- Location where drainage cross section was measured (actual plots and measurements available in ArcView and Excel datafile)
- Thalweg
- Catchment area
- Cultural area
- Eolian deposit
- High-flow sand deposit
- Flood-flow sand deposit
- Pre-dam alluvium
- Alluvium of puebloan age
- Debris fan: lobe
- Alluvial fan
- Talus
- Bedrock-Proterozoic Dox Formation

N

10 0 10 20 Meters



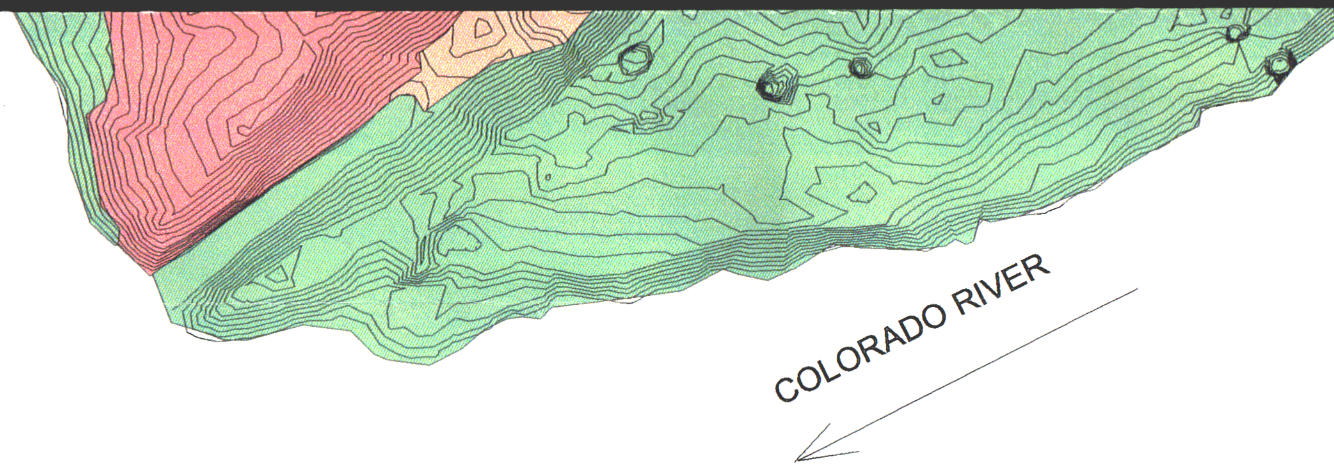
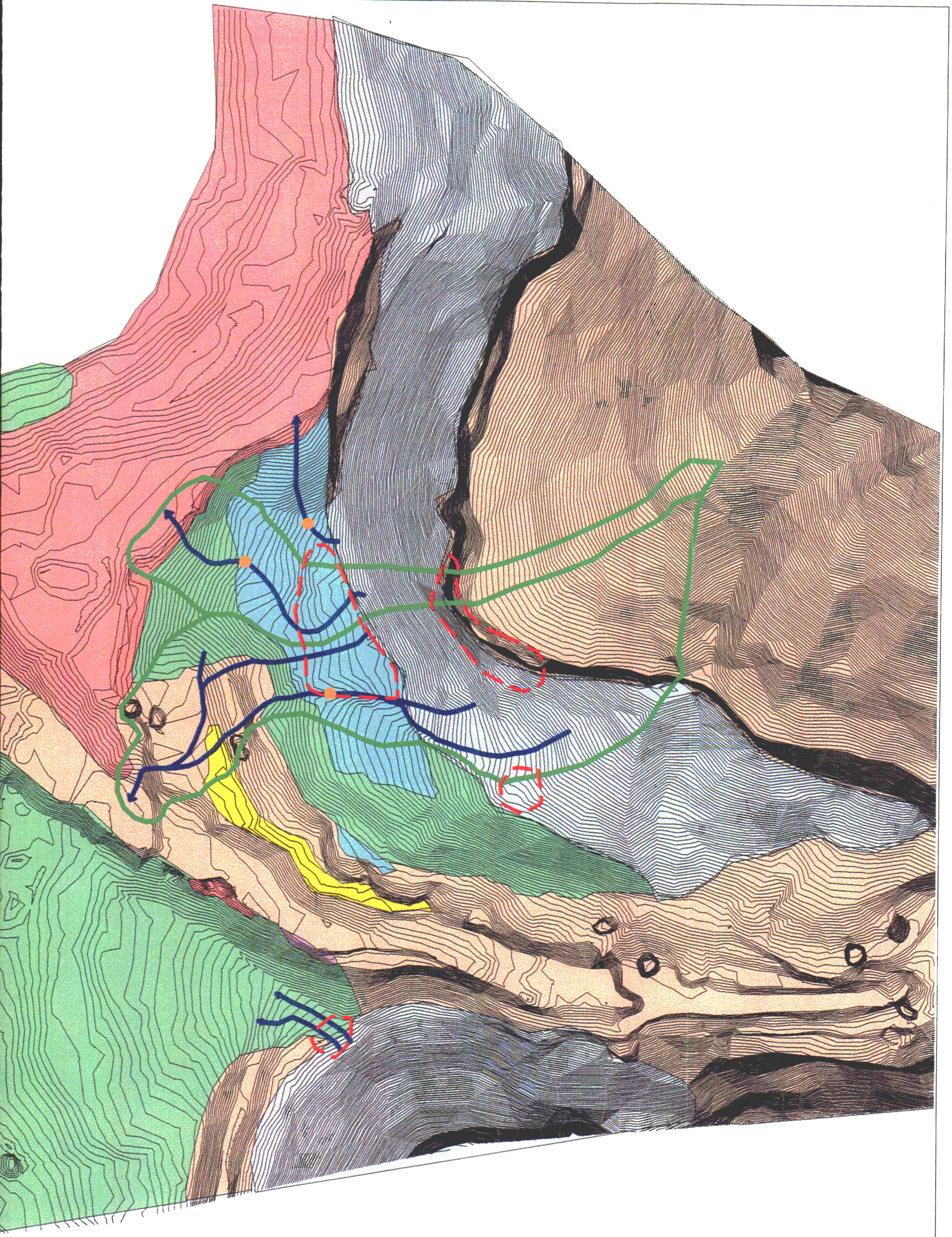


Plate 5. 122 MILE CANYON FAN LOBE GEOMORPHIC SETTING

- Location where drainage cross section was measured (actual plots and measurements available in ArcView and Excel datafiles)
- Thalweg
- Catchment area
- Cultural area
- Flood flow sand deposit
- Pre-dam alluvium
- Lower mesquite terrace
- Alluvium of puebloan age
- River gravel
- Debris fan: lobe
- Talus
- Bedrock-Cambrian Tonto Group

N

5 0 5 10 Meters



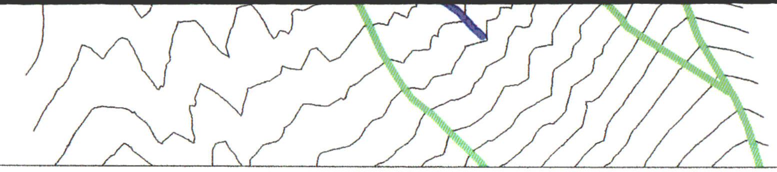
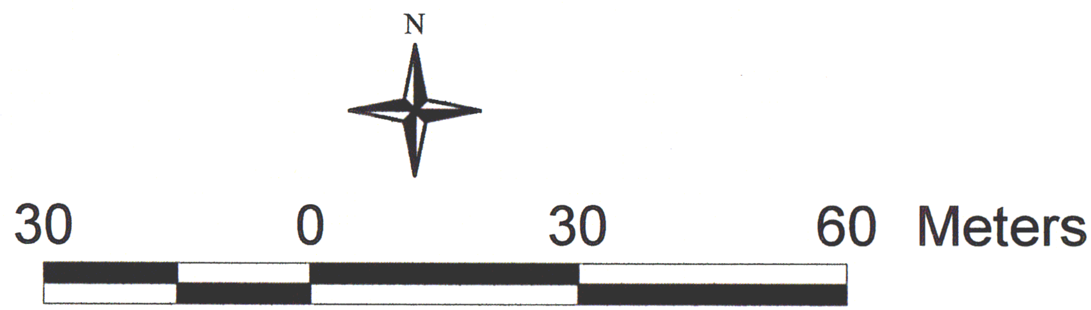
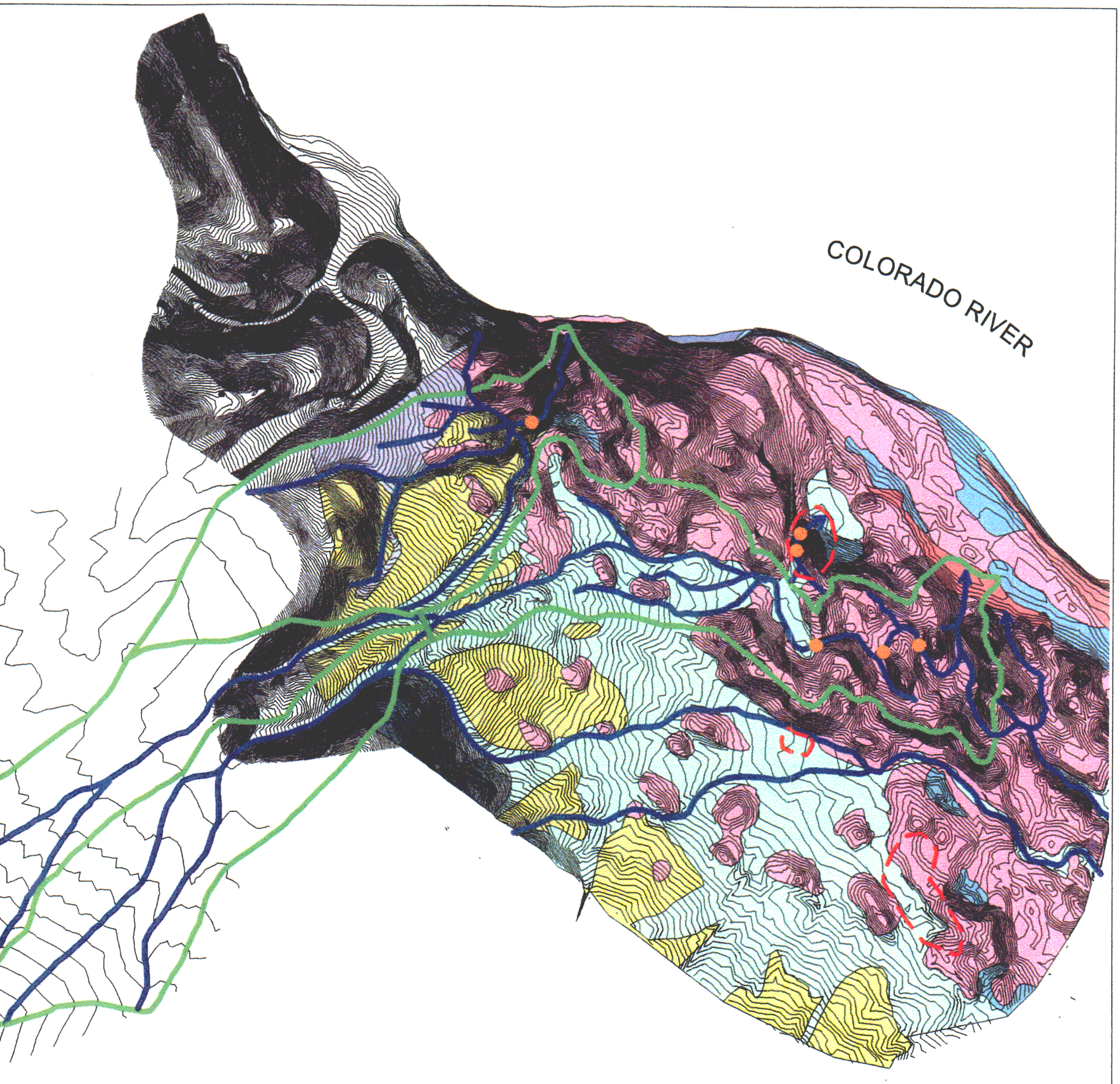


Plate 6. LOWER TANNER DUNE FIELD GEOMORPHIC SETTING

- Location where drainage cross section was measured (actual plots and measurements available in Arcview and Excel datafiles)
- Thalweg
- Catchment area
- Cultural area
- Eolian deposit
- High-flow sand deposit
- Flood-flow sand deposit
- Pre-dam alluvium
- Alluvium of puebloan age
- Striped alluvium
- River gravel
- Debris fan: deltaic
- Alluvial fan
- Talus
- Bedrock-Proterozoic Dox Formation




COLORADO RIVER