CHARACTERIZATION AND EVALUATION OF CHANNEL AND HILLSLOPE EROSION ON THE ZUNI INDIAN RESERVATION, NEW MEXICO, 1992-95

By Allen C. Gellis

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CONTENTS

Page
Abstract ... 1
Introduction ... 1
Purpose and scope ... 2
Acknowledgments ... 2
Description of the study area ... 2
Location and setting ... 2
Erosion on the Zuni Indian Reservation ... 2
Previous studies of channel erosion ... 4
Hydrologic and climatic conditions during the study period ... 6
Methods of data collection and interpretation ... 6
Channel erosion data ... 6
Hillslope erosion data ... 13
Channel erosion ... 17
Hillslope erosion ... 39
Summary ... 49
References ... 49
Appendix--Selected references on erosion control and watershed rehabilitation ... 51

FIGURES

1. Maps showing location of the Zuni Indian Reservation, New Mexico, and U.S. Geological Survey streamflow-gaging stations and rain gages ... 3
2. Diagrams showing arroyo evolution. (A) Changes at a cross section over time following channel incision. (B) Hypothetical changes in sediment production and active-channel (gully) drainage density over time as an arroyo evolves from stage "a" through stage "f" ... 5
3. Maps showing: (A) delineation of the Rio Nutria watershed within the Zuni Indian Reservation, New Mexico, and (B) location of subbasins in the Rio Nutria watershed ... 8
4. Maps showing location of surveyed reaches, streamflow-gaging stations, and rain gages in (A) Y-Unit Draw, (B) Conservation Draw, and (C) Benny Draw ... 10
5. Cross section showing example of top width and depth measurements at cross section CD3AB ... 13
6. Map showing sediment trap sites, 1992-94, and land cover in the Rio Nutria watershed ... 14
7. Photographs showing typical land-cover types in the Rio Nutria watershed: (A) sheep grazing in mixed-grass pasture in the upper Nutria watershed, (B) collection of sediment from sediment trap at mixed-grass pasture site PA-1, (C) chained piñon and juniper site CH-1, and (D) sagebrush site SA-1 with sediment trap ... 15
8. Graphs showing distribution of slopes for land-cover types ... 18
9. Graphs showing top width-to-depth ratios, surveyed in 1992, along (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries ... 19
10. Graphs showing depth, surveyed in 1992, along (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries ... 22
11. Graphs showing top width, surveyed in 1992, along the main channel of (A) Y-Unit Draw, (B) Conservation Draw, and (C) Benny Draw ... 25
12. Photographs showing changes in the main-channel geometry of Conservation Draw in an upstream direction and in tributary CDT3: (A) CD1, (B) CD5, (C) CD9, (D) CD12, and (E) CDT3 ... 26
13. Graphs showing changes in depth between 1992 and 1995 for resurveyed cross sections in (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries ... 30

Page
14. Graph showing distribution of aggradation between 1992 and 1995 for all resurveyed cross sections 33
15. Histograms showing relation between width-to-depth ratio and mean change in cross-sectional area between 1992 and 1995 for all resurveyed cross sections 36
16. Diagrams showing relation between scour greater than 0.05 meter between 1992 and 1995 for all resurveyed cross sections and (A) top width-to-depth ratio, (B) bottom width-to-depth ratio, and (C) coefficient of geometry 37
17. (A) 1934 gully map of Rio Nutria drawn from 1:28,000-scale aerial photographs and (B) 1988 gully map of Rio Nutria drawn from 1:15,840-scale aerial photographs 40
18. Box plots showing sediment concentrations in samples collected from sediment traps, 1992-94 47
19. Graph showing volume-weighted sediment concentration for each sediment trap, 1992-94 48
20. Graph showing volume-weighted sediment concentration for each land-cover type, 1992-94 48

TABLES

1. Precipitation on the Zuni Indian Reservation, 1950-94 7
2. Runoff recorded at the U.S. Geological Survey streamflow-gaging station Rio Nutria near Ramah, New Mexico, 1970-94 7
3. Summary of top width-to-depth ratios, surveyed in 1992, upstream and downstream from headcuts in the three surveyed subbasins of the Rio Nutria watershed 34
4. Cross-sectional channel changes in Y-Unit Draw, Conservation Draw, and Benny Draw, 1992-95 34
5. Average changes, 1992-95, in top and bottom width-to-depth ratios for all resurveyed cross sections of (A) increasing cross-sectional area and decreasing cross-sectional area, (B) scour in cross sections and aggrading cross sections, (C) widening at top of channel and nonwidening cross sections, and (D) widening at bottom of channel and nonwidening 35
6. Features of selected subbasins 42
7. Characteristics of sediment trap sites and summary of data 43

VERTICAL DATUM

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

CHARACTERIZATION AND EVALUATION OF CHANNEL AND HILLSLOPE EROSION ON THE ZUNI INDIAN RESERVATION, NEW MEXICO, 1992-95

By Allen C. Gellis

Abstract

Like many areas of the southwestern United States, the Zuni Indian Reservation, New Mexico, has high rates of erosion, ranging from 95 to greater than 1,430 cubic meters per square kilometer per year. Erosion on the Zuni Indian Reservation includes channel erosion (arroyo incision and channel widening) and hillslope (sheetwash) erosion. The U.S. Geological Survey conducted a 3-year (1992-95) study on channel and hillslope erosion in the portion of the Rio Nutria watershed that drains entirely within the Zuni Indian Reservation. Results of the study can be used by the Zuni Tribe to develop a plan for watershed rehabilitation.

Channel changes, gully growth, headcuts, and changes in dirt roads over time were examined to characterize and evaluate channel erosion in the Rio Nutria watershed. Channel cross-sectional changes included width, depth, width-to-depth ratio, area, and geometry. Relative rates of gully growth, headcuts, and changes in dirt roads over time were examined using aerial photographs. Results of resurveys conducted between 1992 and 1994 of 85 channel cross sections indicated aggradation of 72 percent of cross sections in three subbasins of the Rio Nutria watershed. Forty-eight percent of resurveyed cross sections showed an increase in cross-sectional area and erosion; nine of these are in tributaries. Some channels (43 percent) aggraded and increased in cross-sectional area. This increase in cross-sectional area is due mostly to widening. Channel widening is a more pervasive form of erosion than channel scour on the Zuni Indian Reservation. The tops of channels widened in 67 percent and the bottoms of channels widened in 44 percent of resurveyed cross sections. Narrow, deep triangular channels are more erosive than rectangular cross sections.

Five land-cover types--three sites on mixed-grass pasture, two sites on unchained piñon and juniper, one site on sagebrush, one site on ponderosa pine, and two sites on chained piñon and juniper--were each instrumented with sediment traps between 1992 and 1994 to measure hillslope erosion. Highest sediment yields were measured at chained areas and mixed-grass pasture. Annual yields from sites that were operated for more than a year were 11.7, 6.0, and 6.5 metric tons per square kilometer per year at a piñon and juniper site, mixed-grass pasture site, and sagebrush site, respectively.

INTRODUCTION

As a result of litigation between the Zuni Tribe and the U.S. Government, the Zuni Land Conservation Act of 1990 was passed. This act obligated the Zuni Tribe to formulate a Zuni Sustainable Resource Development Plan, which, among other mandates, shall include a program of watershed rehabilitation. The act required the development plan to be completed in 2 years. To help develop this program of watershed rehabilitation, the U.S. Geological Survey (USGS) entered into a cooperative agreement with the Pueblo of Zuni.

To develop an approach toward watershed rehabilitation, the Zuni Tribe instituted the Zuni Conservation Project, which included several work groups: range science, fish and wildlife, geographic information system (GIS), forestry, hydrology and erosion, and agriculture. Each group agreed that a pilot watershed should be studied to provide interpretive data that would assist in watershed-rehabilitation and erosion-control strategies. Dr. William Fleming of the University of New Mexico (written commun., October

1993) independently reviewed the study conducted by the hydrology and erosion work group and its usefulness in developing an approach to selecting a watershed for rehabilitation. Because of its importance in the Zuni community and its natural diversity, the Rio Nutria watershed was selected as this pilot watershed. Only results of the studies conducted in the Rio Nutria watershed by the hydrology and erosion work group are presented in this report, which was prepared in cooperation with the Pueblo of Zuni.

Purpose and Scope

This report describes the results of a 3-year USGS study to characterize and evaluate channel and hillslope erosion in the portion of the Rio Nutria watershed that drains entirely within the Zuni Indian Reservation. Results of this study can be used by the Zuni Tribe to develop a program for watershed rehabilitation, which includes development of an approach for selecting the most appropriate watersheds for rehabilitation, appropriate erosion-control strategies, and a program to monitor the effectiveness of erosion-control strategies. References listed in the appendix (at the back of the report) provide additional approaches to, methods of, and case studies on erosion control and watershed rehabilitation.

The Zuni Land Conservation Act of 1990 decreed that only lands in the Zuni Indian Reservation be subject to rehabilitation. Thus, the scope of this report does not extend beyond the Zuni Indian Reservation boundary. This may limit some interpretations because upstream hydrologic and geomorphic factors may affect downstream erosion.

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DESCRIPTION OF THE STUDY AREA

Location and Setting

The Zuni Indian Reservation (fig. 1) is located in the southern portion of the Colorado Plateau physiographic province in western New Mexico (Fenneman, 1931). Landform features are flat-topped or gently sloping mesas, dissected by intermittent and ephemeral streams. Elevations on the reservation range from 1,800 to 2,350 meters (m) above sea level. The climate of the Zuni Indian Reservation is semiarid, and the average annual rainfall reported at Zuni Village is 305 millimeters (mm). Terrestrial habitats consist of mixed shrub, sagebrush, piñon, juniper, cottonwood, willow, and grasslands (U.S. Army Corps of Engineers, 1992). The Zuni Indian Reservation comprises 165,280 hectares (ha), of which the primary land uses are rangeland for sheep and cattle grazing in the valley bottoms and irrigation and dry-land farming. The population of the Zuni Indian Reservation in 1990 was 8,996.

The major drainage of the Zuni Indian Reservation is the Zuni River, which is a tributary to the Little Colorado River and joins it in eastern Arizona. The drainage area of the Zuni River at the Arizona border is 3,403 square kilometers (km^2); about 1,810 km^2 are outside the Zuni Indian Reservation boundary. Principal tributaries of the Zuni River are the Rio Pescado and Rio Nutria (fig. 1). Flow is intermittent in the Zuni River, Rio Nutria, and Rio Pescado. Tributaries to these systems are ephemeral, and runoff results from summer convective storms, snowmelt runoff, and rainfall on snowpack.

Erosion on the Zuni Indian Reservation

Like many areas of the southwestern United States, the Zuni Indian Reservation has high rates of erosion, ranging from 95 to greater than 1,430 cubic meters per square kilometer per year ($m^3/km^2/yr$) (New Mexico Natural Resource Department, 1978). Erosion on the Zuni Indian Reservation includes channel erosion (arroyo incision and channel widening) and hillslope (sheetwash) erosion. An arroyo is a channel incised in alluvial and colluvial material that contributes a large amount of sediment in a semiarid watershed (Leopold and others, 1966). Hillslope erosion is the erosion and transport of soil

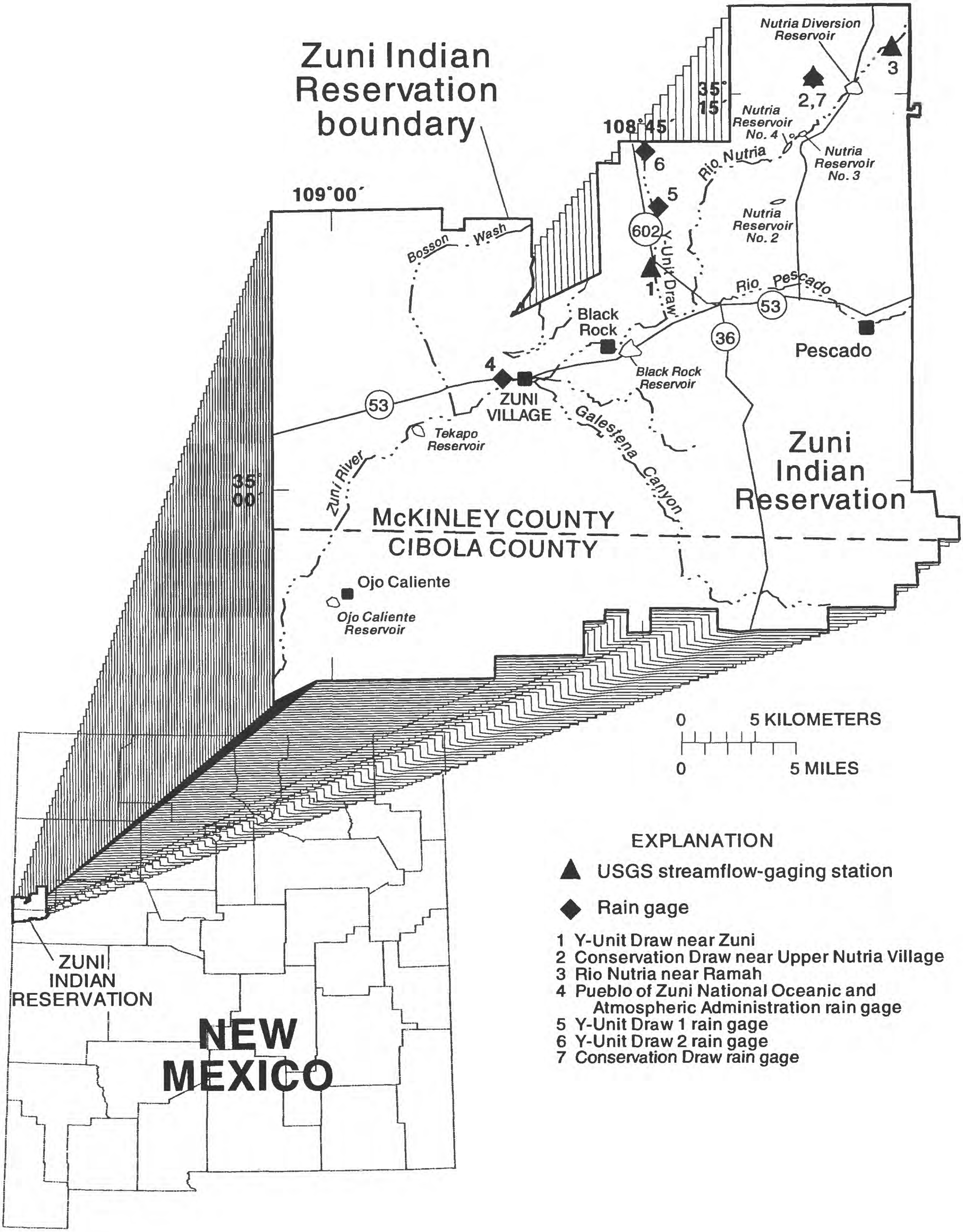


Figure 1.--Location of the Zuni Indian Reservation, New Mexico, and U.S. Geological Survey streamflow-gaging stations and rain gages.

from a hillslope by tiny streams that move back and forth across the hillslope during a rainstorm (Dunne and Leopold, 1978). Sheetwash together with rainsplash is responsible for most hillslope erosion. For the purposes of this report, a hillslope is defined as that part of the watershed not under channelized flow but dominated by sheetwash. By this definition of hillslope, slopes may vary from very flat to steep. Channel widening results from instream flows undercutting the banks, bank slumping, and soil piping.

Recent arroyo incision on the Zuni Indian Reservation began between 1905 and 1920 (Balling and Wells, 1990). Past episodes of alluvial cut-and-fill events on the Zuni Indian Reservation were described by Wells (1987), who identified as many as four episodes of downcutting in Bosson Wash during the periods 7,100 to 6,700; 4,200 to 3,800; 2,800 to 2,400; and 1,300 to 1,000 years before the present. As part of this study, bark from a dead tree rooted to the channel bottom in the upper reaches of Y-Unit Draw (fig. 1) was dated to 680 plus or minus 90 years before the present, indicating the existence of an arroyo at that time.

Today, erosion on the Zuni Indian Reservation is a major problem and is reducing farmland and grazing areas and affecting roads. Sediment transported by arroyos is reducing reservoir capacities, contributing to flooding problems by reducing channel capacities, and degrading wetland habitats.

PREVIOUS STUDIES OF CHANNEL EROSION

A major cycle of erosion occurred in the southwestern United States during the latter part of the 19th century and early part of the 20th century. A considerable debate about the causes of this arroyo development centered on changes in climate, changes in land-use activities, and intrinsic factors, such as a natural cycle of arroyo incision. The contrast between climate and land use led to one of the great geomorphic debates in the Southwest on what caused the arroyo incision episode in the late 1800's to 1920's (Cooke and Reeves, 1976).

The argument that changes in climate cause arroyo incision has focused on changes in precipitation frequency and storm frequency--for example, periods of low rainfall followed by intense summer storm activity (Leopold, 1951; Balling and Wells, 1990). Analysis of climatic records in Santa Fe, New Mexico, by Leopold (1951) indicates that a period of arroyo incision from 1850 to 1880 was characterized by a deficiency of low-intensity rainfall and an increase in the average number of high-intensity rains. Low-intensity rainfall sustains vegetative growth, which may have been depleted between 1850 and 1880. High-intensity rainfall promotes erosion.

The argument that land-use activities cause arroyo incision has centered on overgrazing and timber harvesting (Thornwaite and others, 1942; Cooke and Reeves, 1976). These activities promote increases in surface runoff, which initiates arroyo incision. Graf (1979) concluded that incision of montane arroyos and gullies in the Front Range of Colorado was controlled by the distribution and density of biomass in the basin and by the location of vegetation types on the valley floor. Removal of vegetation in the 1800's in northern Colorado led to the entrenchment of many valleys.

Another argument is that arroyo incision is intrinsic or has a natural cyclicity (Schumm and Hadley, 1957; Patton and Schumm, 1975). This argument contends that arroyo incision would occur regardless of climatic or human-induced changes, although climate and human activities affect the thresholds of incision and filling. Gullying in northern Colorado was found to be related to intrinsic geomorphic factors (Patton and Schumm, 1975). A threshold line relating drainage area and valley slope that separates gullied from ungullied areas was developed from data for several valleys. The steepening of the valley floor by aggradation leads to an increase in valley slope. As the valley floor continues to steepen, a threshold in the slope is exceeded and a gully forms.

Bocco (1991) provided an extensive literature review on gullying. An incised channel or arroyo generally is initiated as a headcut that forms the gully or arroyo and moves upgradient along the valley floor or an existing channel (Schumm and others, 1984). A headcut is a vertical drop in the bed of the gully. Headcut advancement can be related to watershed area, rainfall intensity, and soil properties (Thompson, 1964; Seginer, 1966). Once a gully forms, several decades to tens of decades may pass before a new equilibrium is attained. During this time, the gully or arroyo will go through a series of changes in shape that ultimately lead to a new state of equilibrium (Heede, 1974; Schumm and others, 1984; Gellis, 1992) (fig. 2A). These changes in gully shape follow the advancement of the headcut, from the lower to the upper reaches. Changes in gully shape also can be observed over time

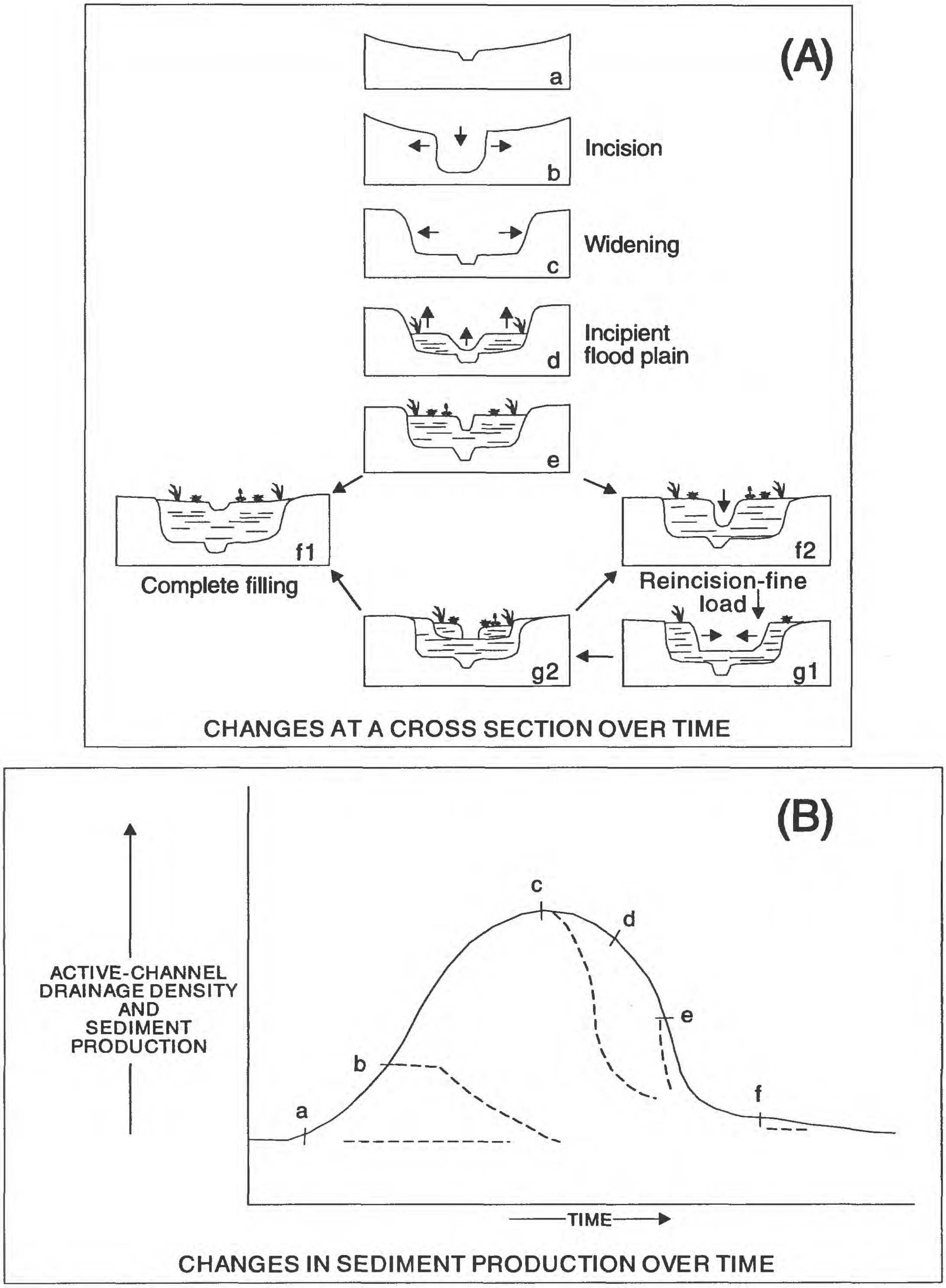


Figure 2.--Arroyo evolution.

(A) Changes at a cross section over time following channel incision. Stages "a" through "g " can represent changes at a cross section over time or changes from the lower reaches to the upper reaches of the watershed at any time (from Gellis, 1992).

(B) Hypothetical changes in sediment production and active-channel (gully) drainage density over time as an arroyo evolves from stage "a" through stage "f". Dashed lines indicate effect of gully-control structures at various times during channel evolution (from Schumm, 1985).

at one selected location in the gully (fig. 2A). Generally, the channel changes over time from a narrow, V-shaped gully with low width-to-depth ratios to a wide, U-shaped gully with high width-to-depth ratios. This pattern of arroyo development over time may have important implications on the selection of strategies for gully and arroyo controls (fig. 2B).

Schumm and others (1984) developed a five-stage channel evolution model for Oaklimeter Creek, Mississippi, that described a distinctive pattern of channel changes as the channel approached a new equilibrium. Conditions of disequilibrium originated in downstream reaches and moved upstream over time. Distinctive stages of channel geometry were observed during the change from disequilibrium to equilibrium. These identified channel stages were used in the decision making process for structural or nonstructural controls. For gullies in Israel, Seginer (1966) found a positive correlation between the distance from the headcut and the downstream gully cross-sectional area.

HYDROLOGIC AND CLIMATIC CONDITIONS DURING THE STUDY PERIOD

The study period was January 1992 through January 1995. Average annual rainfall reported at the National Oceanic and Atmospheric Administration (NOAA) rain gage at Zuni during the study period was 380 mm, which is higher than the long-term (1950-94) average of 315 mm. For 1992 and 1994, precipitation was 49 percent and 16 percent higher, respectively, than average annual rainfall. For 1993, precipitation was 3 percent lower than average annual rainfall (table 1). Convective rainstorms in the summer can cause severe overland flow, channel flow, and erosion (Leopold and others, 1966). Summer precipitation (average total rainfall for July, August, and September) reported at the NOAA rain gage in 1992 was 199 mm, which is higher than the long-term average of 138 mm. Summer precipitation in 1993 and 1994 was 91 and 137 mm, respectively, which is lower than the long-term average (table 1). Therefore, erosion that correlates to summer rainfall may have been lower than average in 1993 but higher than average in 1992.

Average annual runoff for 1992-94 measured at the USGS streamflow-gaging station Rio Nutria near Ramah (09386900) (fig. 1) was 7.78×10^6 cubic meters (m^3), which is higher than the long-term average (1970-94) of 6.06×10^6 m^3 (table 2). For 1992 and 1994, runoff was 24 percent and 59 percent lower, respectively, than the long-term average and in 1993 was 168 percent higher than the long-term average (table 2). Differences in precipitation and runoff during the study period compared with long-term averages could reflect the difference in the lengths of record; the record is longer for precipitation. Although precipitation at Zuni Village was lower than average in 1993, runoff for Rio Nutria near Ramah was higher than average because runoff was extremely high during January, February, and March of 1993. This high runoff was due possibly to a high snowpack. Differences also could be the result of the spatial distribution of rainfall.

Streamflow stations were installed in Conservation Draw (09386910) (drainage area 6.40 km^2) and Y-Unit Draw (09386925) (drainage area 24.55 km^2) in May 1992 and July 1992, respectively (fig. 1). From May 14, 1992, to September 30, 1994, Conservation Draw had flow on 36 days and a total runoff of 197,650 m^3. From July 1, 1992, to September 30, 1994, Y-Unit Draw had flow on 39 days and a total runoff of 68,550 m^3. The highest peak flow recorded at Y-Unit Draw was 0.27 m^3/s on July 10, 1992. At Conservation Draw the highest peak flow recorded was 8.07 m^3/s on August 11, 1992.

METHODS OF DATA COLLECTION AND INTERPRETATION

Channel Erosion Data

Channel changes, gully growth, headcuts, and changes in dirt roads over time were examined to characterize and evaluate channel erosion in and among selected subbasins of the Rio Nutria watershed (fig. 3). Channel cross-sectional changes included width, depth, width-to-depth ratio, area, and geometry. Relative rates of gully growth over time were examined using 1934 and 1988 aerial photographs. Headcuts are important indicators of erosion because they represent base-level lowering of the channel and rejuvenation of the drainage systems. Headcuts were identified from 1988 aerial photographs and field reconnaissance. Changes in dirt roads also were examined using 1934 and 1988 aerial photographs.

Table 1.--Precipitation on the Zuni Indian Reservation, 1950-94

[NOAA, National Oceanic and Atmospheric Administration]

Rain gage	Time period	Rainfall (millimeters)	Total rainfall for July, August, and September (millimeters)
Zuni (NOAA) rain gage	1950-94	315	138
Zuni (NOAA) rain gage	1992-94	380	142
Zuni (NOAA) rain gage	1992	468	199
Zuni (NOAA) rain gage	1993	307	91
Zuni (NOAA) rain gage	1994	365	137
Conservation Draw	July 1, 1992 - Nov 12, 1992	206	192
Conservation Draw	Mar 15, 1993 - Nov 10, 1993	157	92
Conservation Draw	Mar 16, 1994 - Nov 7, 1994	150	16
Y-Unit Draw-1	June 11, 1992 - Nov. 12, 1992	192	132
Y-Unit Draw-1	Mar 15, 1993 - Nov 15, 1993	267	156
Y-Unit Draw-1	Mar 16, 1994 - June 20, 1994	61	
Y-Unit Draw-2	Aug 20, 1992 - Nov 12, 1992	117	
Y-Unit Draw-2	Mar 15, 1993 - Nov 15, 1993	237	141
Y-Unit Draw-2	Mar 16, 1994 - June 20, 1994	79	

Table 2.--Runoff recorded at the U.S. Geological Survey streamflow-gaging station Rio Nutria near Ramah, New Mexico, 1970-94

Time period	Annual runoff (cubic meters)
1970-94	6.06×10^6
1992-94 (period of study)	7.78×10^6
1992	4.59×10^6
1993	1.62×10^7
1994	2.48×10^6

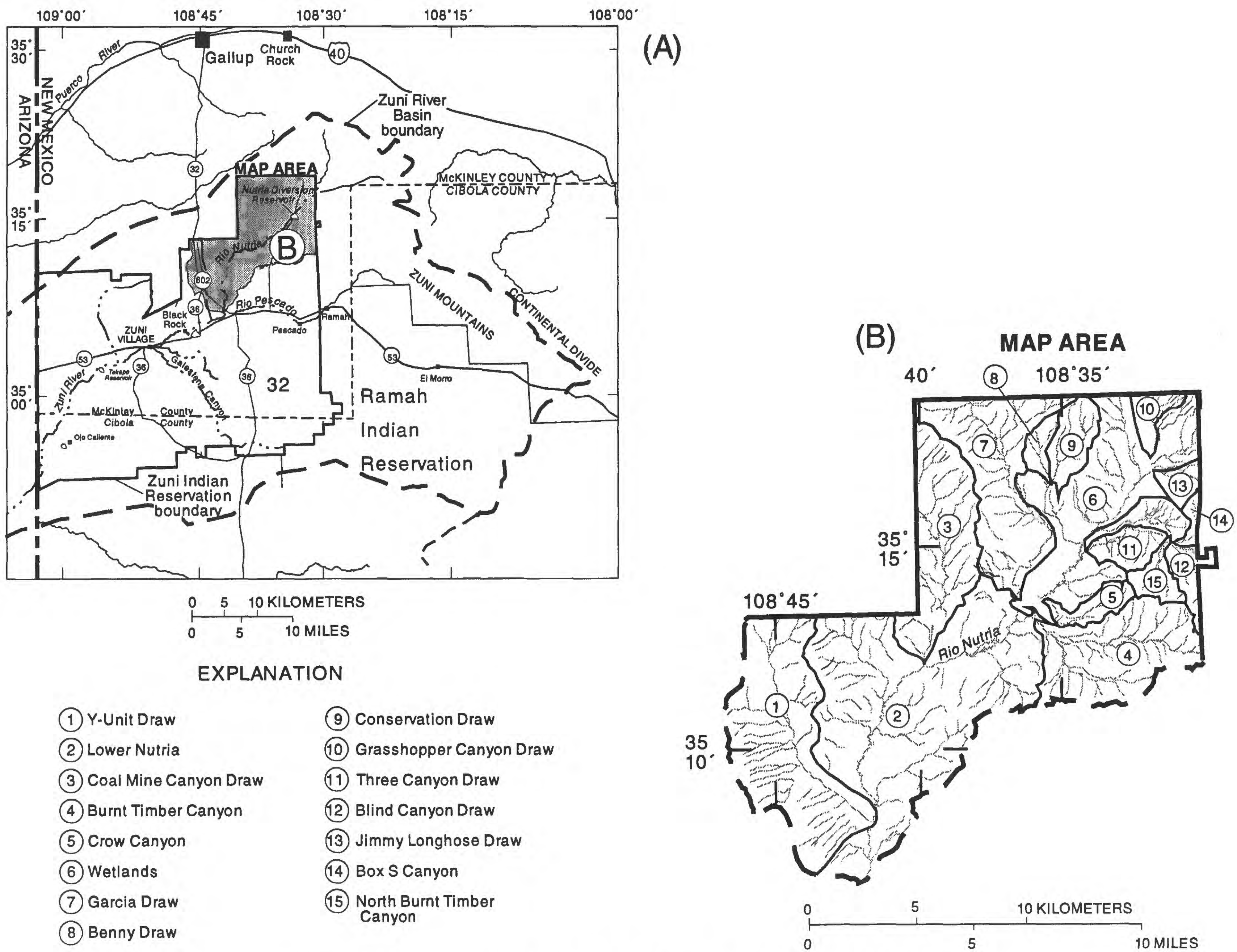


Figure 3.--(A) Delineation of the Rio Nutria watershed within the Zuni Indian Reservation, New Mexico, and (B) location of subbasins in the Rio Nutria watershed.

From January 1992 through January 1995 changes in channel cross sections were examined in three subbasins of the Rio Nutria: Y-Unit Draw, Conservation Draw, and Benny Draw (fig. 4). Reaches were selected in the main channel of each subbasin for channel cross-section surveying; tributaries also were selected in Conservation and Benny Draw. Reaches selected for surveying generally were 300 m apart, but were spaced more closely if channel geometry appeared to change in a short distance. Reaches were located using a Geographic Positioning System (GPS).

In each reach at least two cross sections (and in some reaches as many as six cross sections) were monumented for resurveying. Cross sections generally were spaced a channel width apart. A steel bar was driven into the ground at each end of the cross section on the highest surface (terrace) adjacent to the channel. A tape was stretched across the channel from steel bar to steel bar. Survey shots were taken at 10 evenly spaced points and at breaks in slope in the cross section. Resurveys were performed in the same manner, and the tape was stretched from bar to bar the same distance as for the original survey. Third-order-level survey accuracies were used (Brinker, 1969).

The three subbasins were initially surveyed in 1992 and 1993 and resurveyed at selected times. Only changes in those cross sections resurveyed in 1994 and 1995 are reported here. For Y-Unit Draw, 54 cross sections were initially surveyed between February 6 and April 16, 1992; 31 of these cross sections were resurveyed between June 16, 1994, and January 3, 1995. For Conservation Draw, 51 cross sections were initially surveyed between June 8 and November 4, 1992; 30 of these cross sections were resurveyed between June 24 and July 21, 1994. For Benny Draw, 27 cross sections were surveyed between June 28 and August 3, 1993; 24 of these cross sections were resurveyed between August 25 and November 9, 1994. Eleven of the 30 resurveyed cross sections in Conservation Draw and 4 of the 24 resurveyed cross sections in Benny Draw were located in tributaries.

At all resurveyed cross sections, changes in width were quantified at two depths in the channel: at the top of the channel and near the bottom (fig. 5). The top of the channel is defined as the elevation of the left or right terrace, whichever has the lower elevation. The bottom of the channel is defined as 75 percent of the distance from the top of the channel to the thalweg or lowest part of the channel. Width-to-depth ratios were calculated for the top and bottom of each cross section (fig. 5) from the first surveys. Changes in depth that occurred between surveys were measured relative to the difference in elevation from the left-bank steel bar to the thalweg.

Changes in cross-sectional area of the channel were quantified from the resurveys. The cross-sectional area is the area of the channel defined from a line drawn across the top of the two steel bars that encompasses the channel.

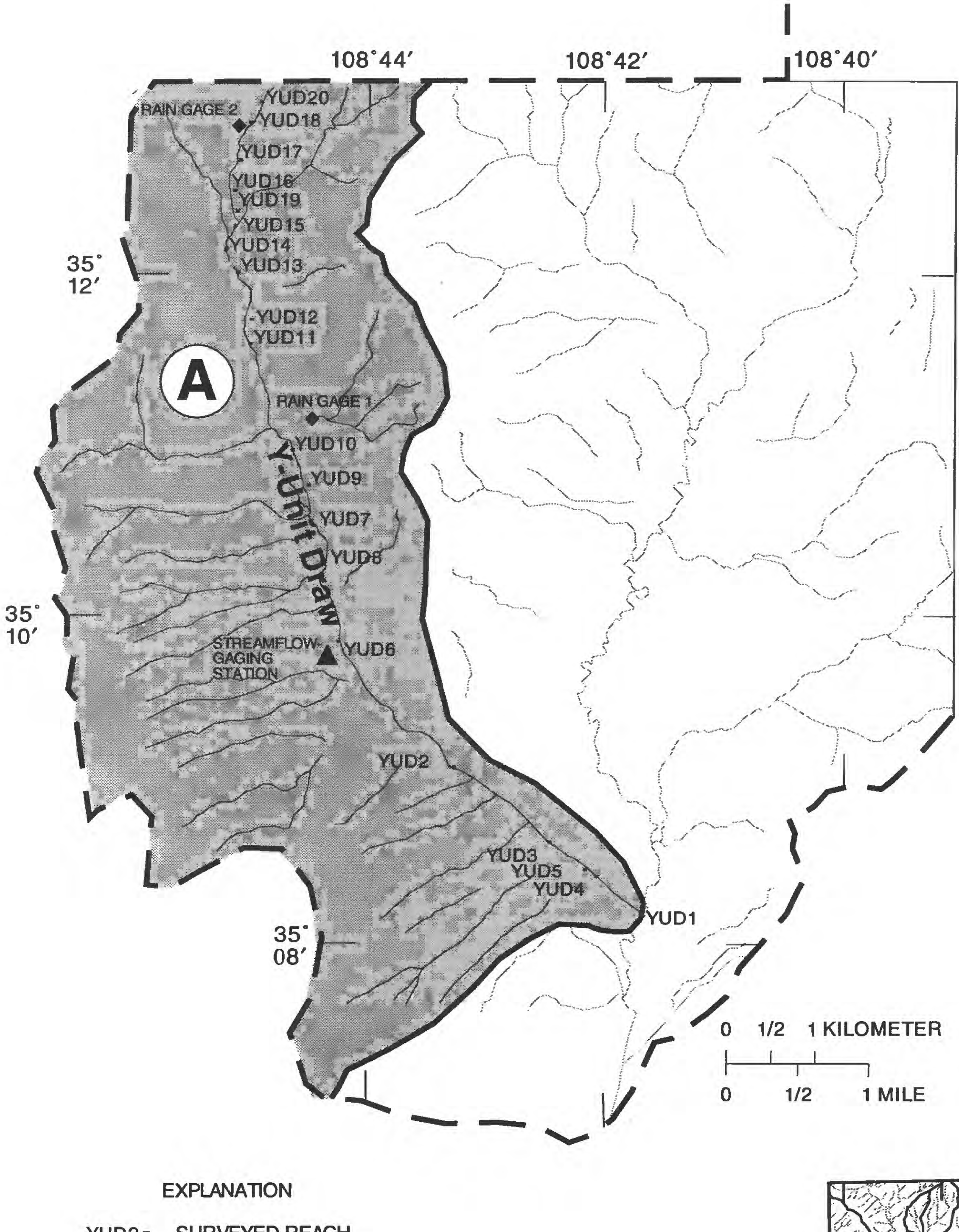
A measure of the shape of the cross section, whether triangular or rectangular, is defined as the "coefficient of geometry." The coefficient of geometry was calculated for each cross section by comparing the area of the channel, defined as the cross section between the edge of the left and right terrace, to the area of a triangle with the same width and depth:

$$\text{Coefficient of geometry} = \frac{(\text{cross-sectional area} - 1/2 \text{ top width} \times \text{depth})}{1/2 \text{ top width} \times \text{depth}} \quad (1)$$

Values closer to 0 indicate triangular cross sections and values closer to 1 indicate rectangular cross sections. Depth of the channel is measured from the top of the channel.

A map of gully systems in 1934 was created from black and white aerial photographs (scale 1:28,000), and a map of gully systems in 1988 was created from 1988 color aerial photographs (scale 1:15,840) (see fig. 17). Changes in the total lengths of gullies over time may indicate basins having greater rates of erosion (Nordstrom, 1988). Subbasins 10, 13, and 14 (fig. 3B) were not covered by the 1934 aerial photographs. Although the quality of the 1934 photos is generally very good, there is some subjectiveness in defining a gully from aerial photos. The 1988 color aerial photographs also were used to identify headcuts in the Rio Nutria watershed.

A map of dirt roads in 1934 in the Rio Nutria watershed was created from black and white aerial photographs (scale 1:28,000), and a map of dirt roads in 1988 was created from color aerial photographs (scale 1:15,840). An increase in dirt road lengths per unit area is an indicator of the potential for increased erosion because dirt roads can channel runoff, possibly leading to gully erosion (Okogbue and Agboo, 1990; Gellis, 1996). Subbasins 10, 13, and 14 (fig. 3B) were not covered by the 1934 aerial photographs. The accuracy of the road coverage generally is good.



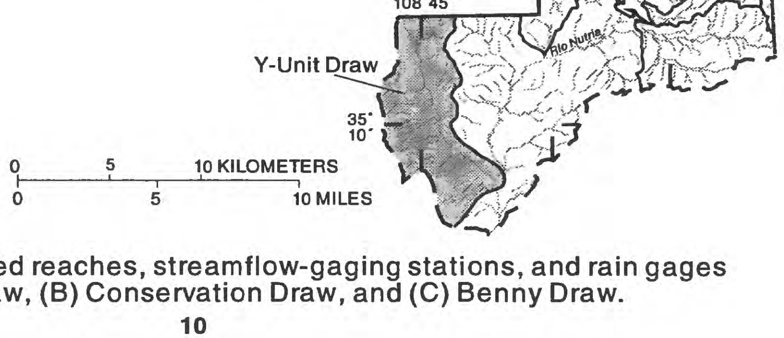


Figure 4.--Location of surveyed reaches, streamflow-gaging stations, and rain gages in (A) Y-Unit Draw, (B) Conservation Draw, and (C) Benny Draw.

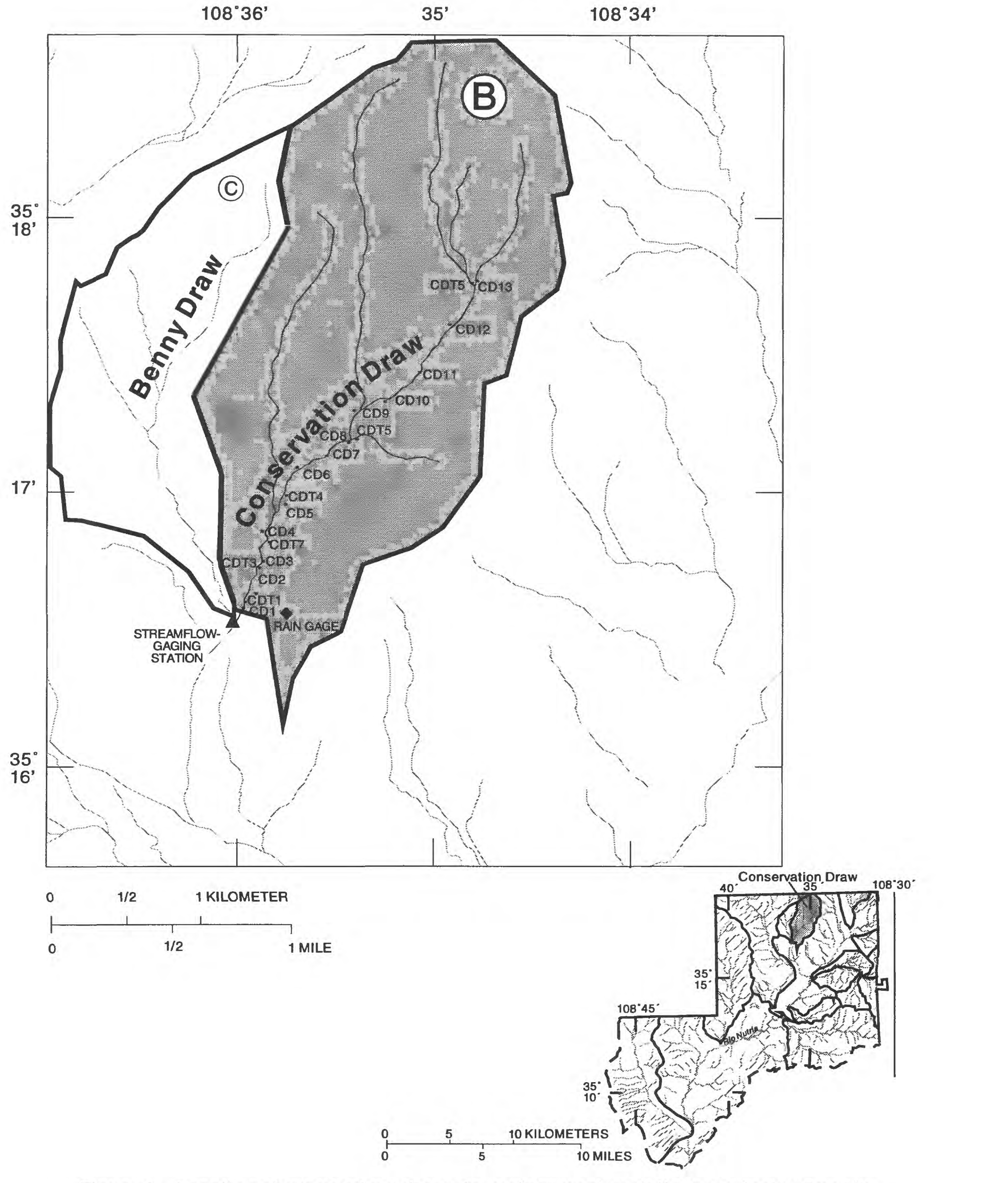


Figure 4.--Location of surveyed reaches, streamflow-gaging stations, and rain gages in (A) Y-Unit Draw, (B) Conservation Draw, and (C) Benny Draw--Continued.

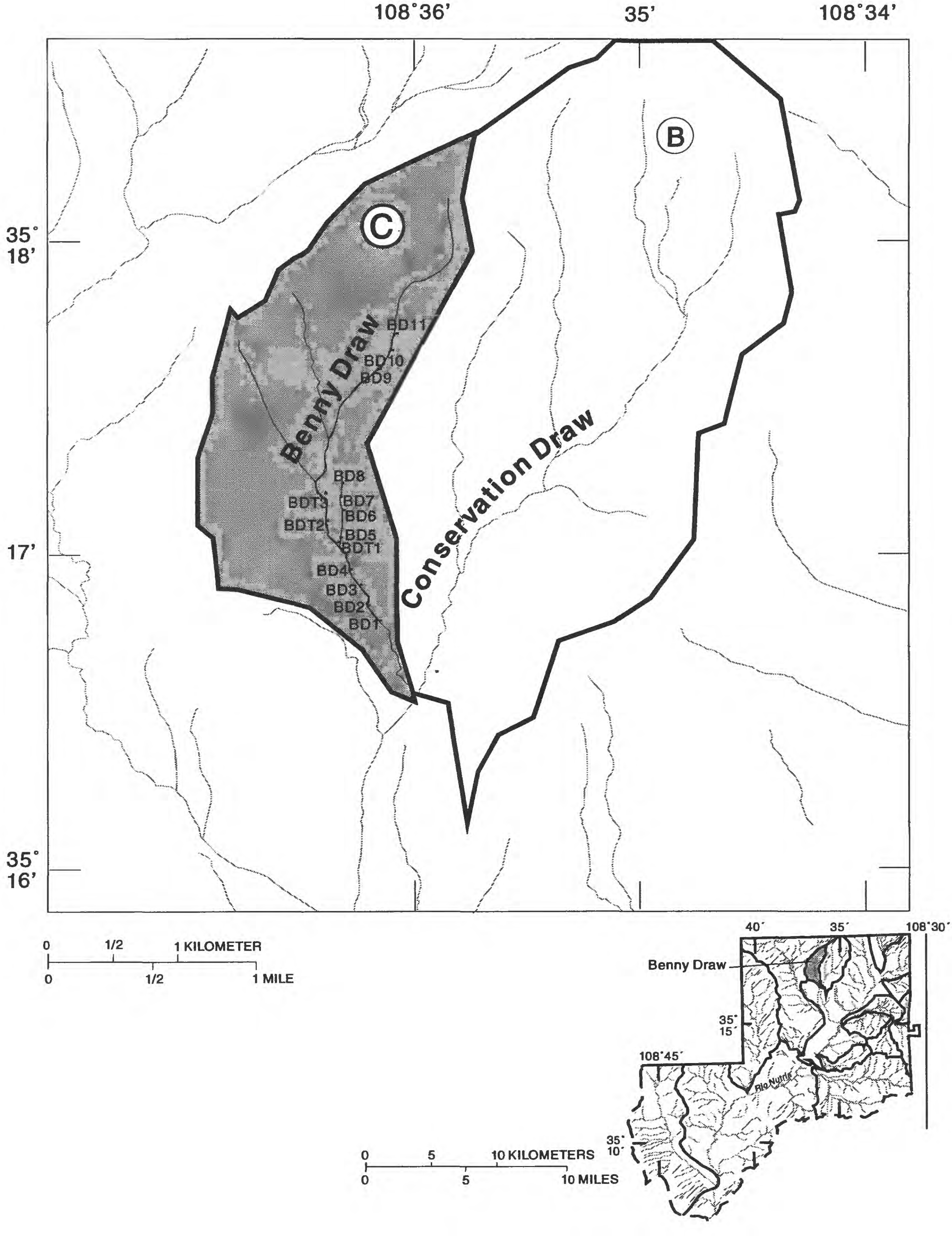


Figure 4.--Location of surveyed reaches, streamflow-gaging stations, and rain gages in (A) Y-Unit Draw, (B) Conservation Draw, and (C) Benny Draw--Concluded.

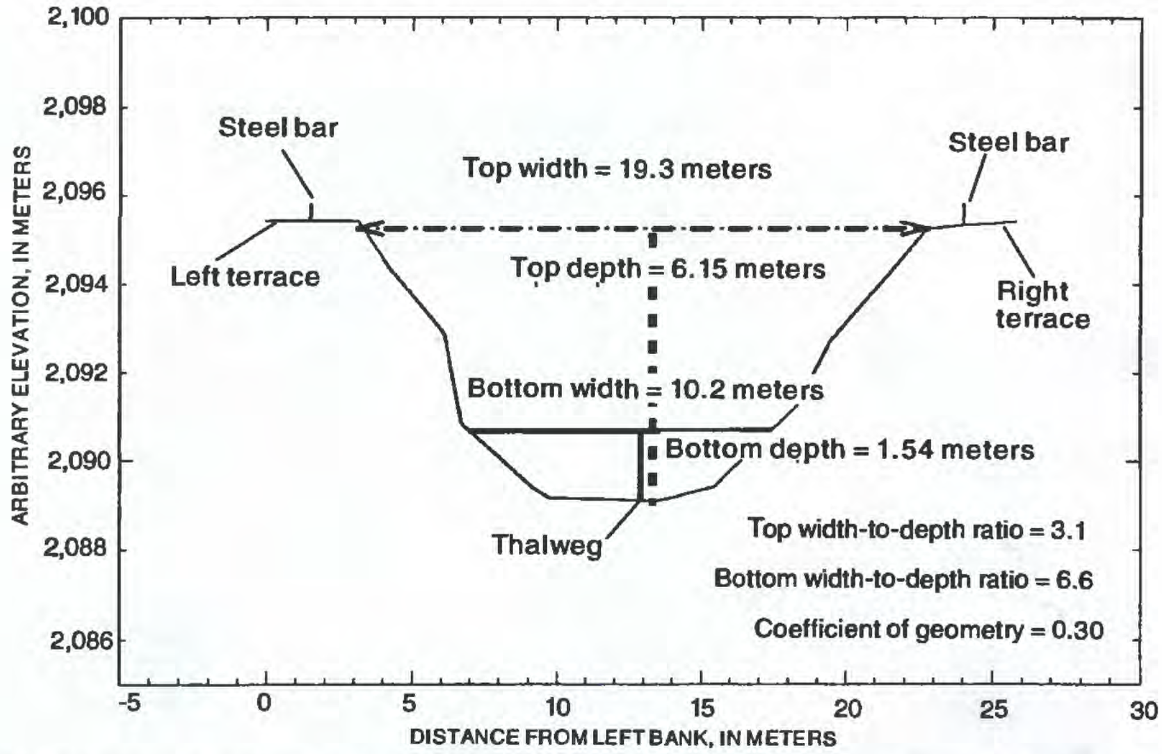


Figure 5.--Example of top width and depth measurements at cross section CD3AB.

Hillslope Erosion Data

Hillslope erosion was measured on selected land-cover types in the Rio Nutria watershed from 1992 to 1994 using sediment traps. Five land-cover types (mixed-grass pasture, unchained piñon and juniper, sagebrush, ponderosa pine, and chained piñon and juniper) were instrumented with sediment traps based on a modified Gerlach Trough (Gerlach, 1967). Chaining is a procedure used to clear vegetation, such as piñon and juniper, to support a more desirable vegetation. Chaining was conducted throughout the Zuni Indian Reservation primarily from 1960 to 1980 to increase grass cover. Many of the chained piñon and juniper sites on the Zuni Indian Reservation have not supported grass and contain large areas of bare ground. Ponderosa pine and unchained piñon and juniper sites contain large areas of vegetative cover, fallen woody debris, and leaf litter. From June 4, 1992, to May 26, 1994, sediment traps collected sediment and runoff during rainfall events. The width of the traps was 52 centimeters (cm) and the depth was 3.3 cm. To prevent precipitation from entering the trap directly, a lid made of sheet metal was fitted with a hinge to the back of the trap. Two 1/2-inch- (1.27-cm) diameter holes were drilled into the side of the trap, one at the bottom and one at half the depth, and fitted with a 3/4-inch (1.90-cm) hose barb. Both holes were connected by tubing to a 5-gallon (18.9-liter) collection bucket. The upper hole was designed to operate if the bottom hole became clogged with organic debris. The traps were installed flush to the ground surface with the opening parallel to the slope contour.

By using a land-cover map generated for the Rio Nutria watershed, nine sites on five principal land-cover types were selected for installation of sediment traps (fig. 6). The land-cover map was traced from 1988 1:15,840-scale color aerial photographs and digitized into a GIS. Land cover for the portion of the Rio Nutria watershed that drains entirely within the Zuni Indian Reservation in 1988 was:

Mixed-grass pasture - 24,900 ha,
Unchained piñon and juniper - 12,300 ha,
Sagebrush - 1,600 ha,
Ponderosa pine - 1,030 ha,
Agriculture - 860 ha, and
Chained piñon and juniper - 300 ha.

Instrumented sites included three mixed-grass pasture sites, two unchained piñon and juniper sites, one sagebrush site, one ponderosa pine site, and two piñon and juniper sites that were extensively chained. Photos of sites typical of land-cover types instrumented with Gerlach Troughs--two mixed-grass pasture sites, a chained piñon and juniper site, and a sagebrush site--are shown in figure 7.

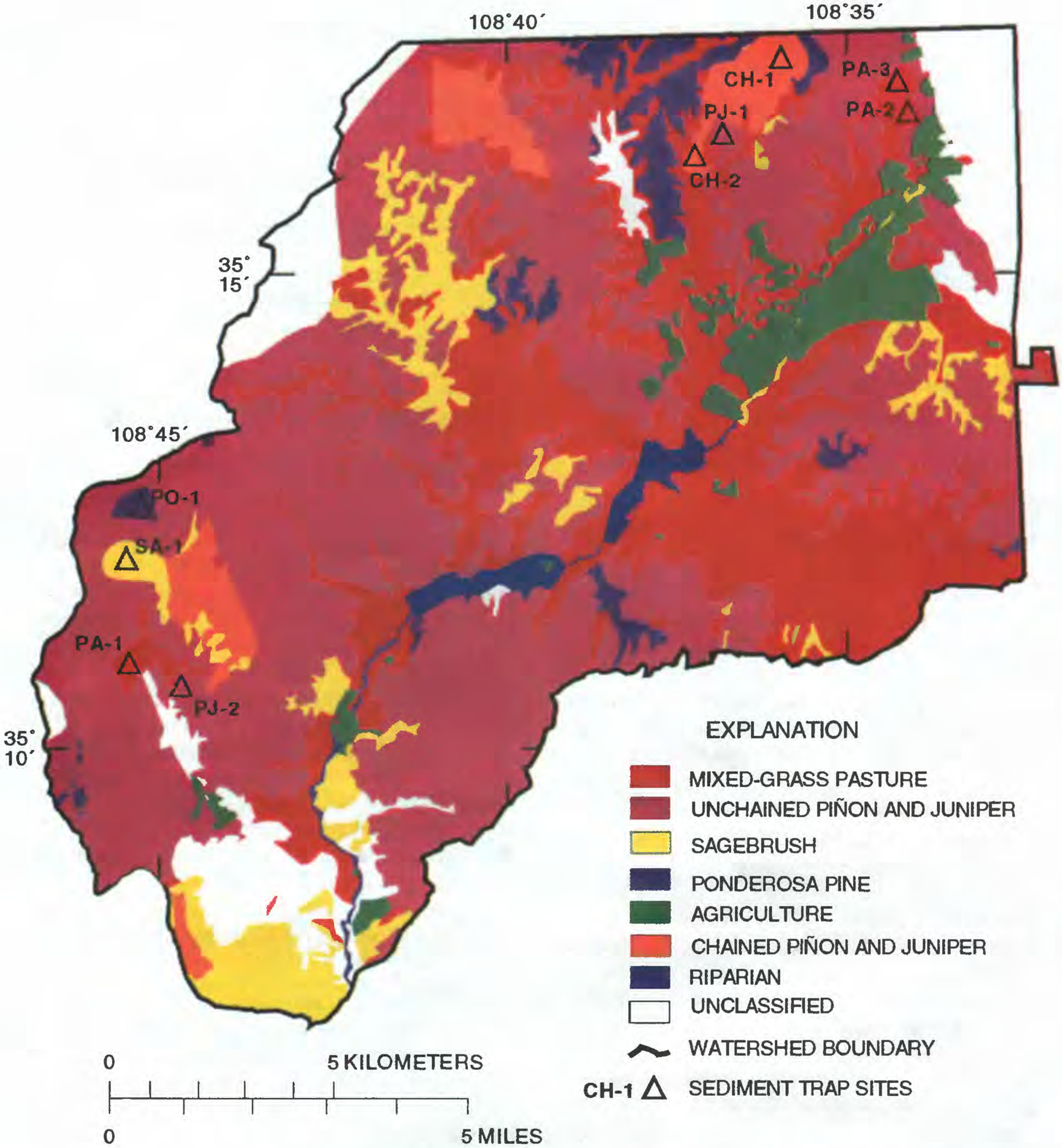


Figure 6.--Sediment trap sites, 1992-94, and land cover in the Rio Nutria watershed (delineated from 1988 aerial photographs).

(A)

Photo: May 1993

(B)

Photo: March 1993

Figure 7.--Typical land-cover types in the Rio Nutria watershed: (A) sheep grazing in mixed-grass pasture in the upper Nutria watershed, (B) collection of sediment from sediment trap at mixed-grass pasture site PA-1, (C) chained piñon and juniper site CH-1, and (D) sagebrush site SA-1 with sediment trap.

(C)

Photo: June 1993

(D)

Photo: June 1993

Figure 7.--Typical land-cover types in the Rio Nutria watershed: (A) sheep grazing in mixed-grass pasture in the upper Nutria watershed, (B) collection of sediment from sediment trap at mixed-grass pasture site PA-1, (C) chained piñon and juniper site CH-1, and (D) sagebrush site SA-1 with sediment trap--Concluded.

All sites instrumented with sediment traps were grazed with either cattle, sheep, or horses, although grazing pressure is higher at pasture sites than at other land-cover sites. An animal unit month (AUM) is defined as a 900- to 1,000-pound (408- to 454-kilogram (kg)) animal grazing for 1 month; the AUM's for each site listed in table 7 are reported as "animal livestock density." Five sheep are considered equal to one cow. Although land-cover sites PA-2 and PA-3 are grazed, AUM's could not be estimated because the land users were not granted a permit.

Three sediment traps were installed on each site (fig. 6). Contributing areas to each trap were not bounded. To determine contributing area, each hillslope was surveyed. The coordinates and elevation of each surveyed point were entered into a computer software package, and a topographic map was generated for each trap. The contributing area was then delineated and digitized to compute contributing area and slope. There may be some error in defining the contributing area of each trap by surveying the hillslope because the divide for the contributing area on a hillslope may be a subtle feature that can be missed in the survey. This method for estimating drainage area is not fully satisfactory; therefore, bounding the contributing area to the sediment trap with an impervious material, such as described by Loughran (1989), may be a more satisfactory method. The slope of the contributing area, reported in degrees, is defined as the angle between a horizontal line and a line between the trap and the divide along a line defining the greatest length of the contributing area.

The distribution of slopes for the five land-cover types instrumented with sediment traps was determined using a GIS. Elevation for the area was obtained from a USGS standard 7.5-minute digital elevation model (DEM) with a 30- by 30-m resolution grid. To improve accuracy, the grid was resampled down to a 10- by 10-m grid. The DEM coverage was obtained from the Earth Resources Observation Systems (EROS) data center in South Dakota.

The distribution of slopes for each land-cover type is shown in figure 8. The average weighted slope for each land-cover type is:

Mixed-grass pasture - 9.4 percent,
Unchained piñon and juniper - 16.9 percent,
Sagebrush - 11.8 percent,
Ponderosa pine - 15.2 percent, and
Chained piñon and juniper - 8.1 percent.

The sediment traps were located on slopes that closely represent the mean slope for each land-cover type (fig. 6). The sediment traps for ponderosa pine were placed on slopes that are higher than average.

Data collected at the sediment trap sites include total sediment (dry weight of sediment), in grams, and total runoff (total weight (mass) of water and sediment runoff to the trap), in grams. After a rain event, personnel in the field first weighed each bucket with a hand scale. Any sediment deposited in the trough was emptied into the bucket. To ease collection, some of the water was poured out of the bucket and weighed again. Sediment that was in suspension was assumed to be insignificant. The remaining water and sediment was brought to the lab. The sediment concentration, in parts per million (ppm), was calculated by dividing the dry weight of sediment, in grams, by the weight of sediment and water and multiplying by 1,000,000.

Three cumulative rain gages were installed in the Rio Nutria watershed (fig. 1; table 1) and read between trap collection periods. When the collection dates for the traps did not coincide with the rain-gage readings, rainfall data from the NOAA weather service rain gage at Zuni Village were used instead (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1992-94). The weather service rain gage is located 15.3, 30.6, and 37.0 km, respectively, from the three cumulative rain gages.

CHANNEL EROSION

Top width-to-depth ratios were derived from initial channel surveys of Y-Unit Draw, Conservation Draw, and Benny Draw in 1992 (fig. 9A-C). In all three subbasins top width-to-depth ratios immediately downstream from headcuts are low relative to upstream from headcuts (fig. 9; table 3). The channel deepens downstream from a headcut, reaching a maximum depth at 415 m downstream from the headcut in Y-Unit Draw, 527 m in Conservation Draw, and 366 m in Benny Draw (fig. 10A-C). Top width increases downstream from a headcut; in Y-Unit Draw the maximum top width of 65.6 m is 1,045 m downstream from a headcut, in Conservation Draw the maximum of 21.2 m is 203 m downstream from a headcut, and in Benny Draw the maximum of 21.8 m is 350 m downstream from a headcut (fig. 11A-C). Changes of channel geometry in an upstream direction are depicted for Conservation Draw and tributary CDT3, where an upstream decrease in channel top width and a decrease in vegetation can be observed (fig. 12). A study of gullies in Medicine Creek, Nebraska, showed a gradual decrease in depth downstream from a headcut and a maximum in gully width a thousand feet (305 m) downstream from the headcut (Brice, 1966).

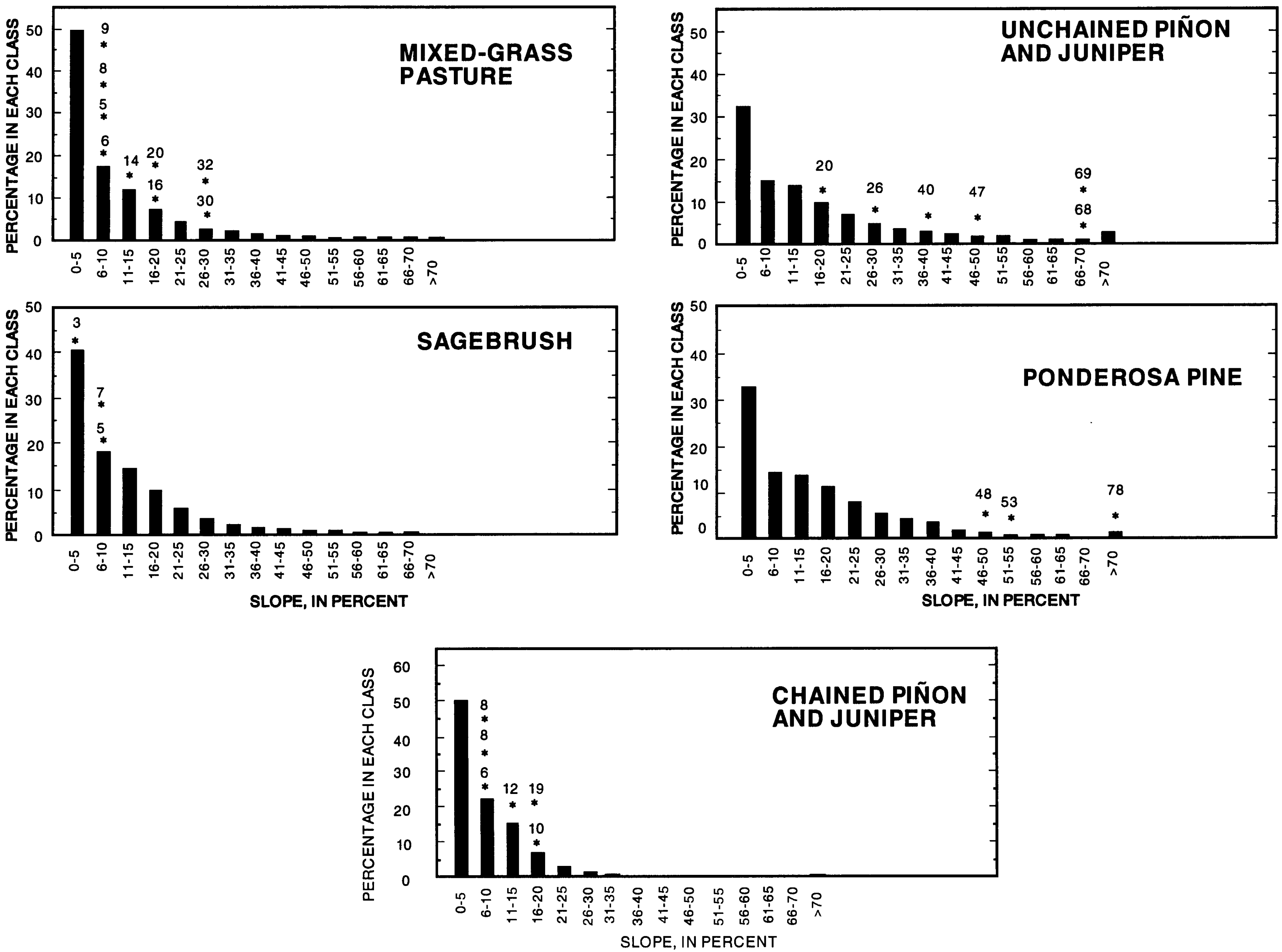
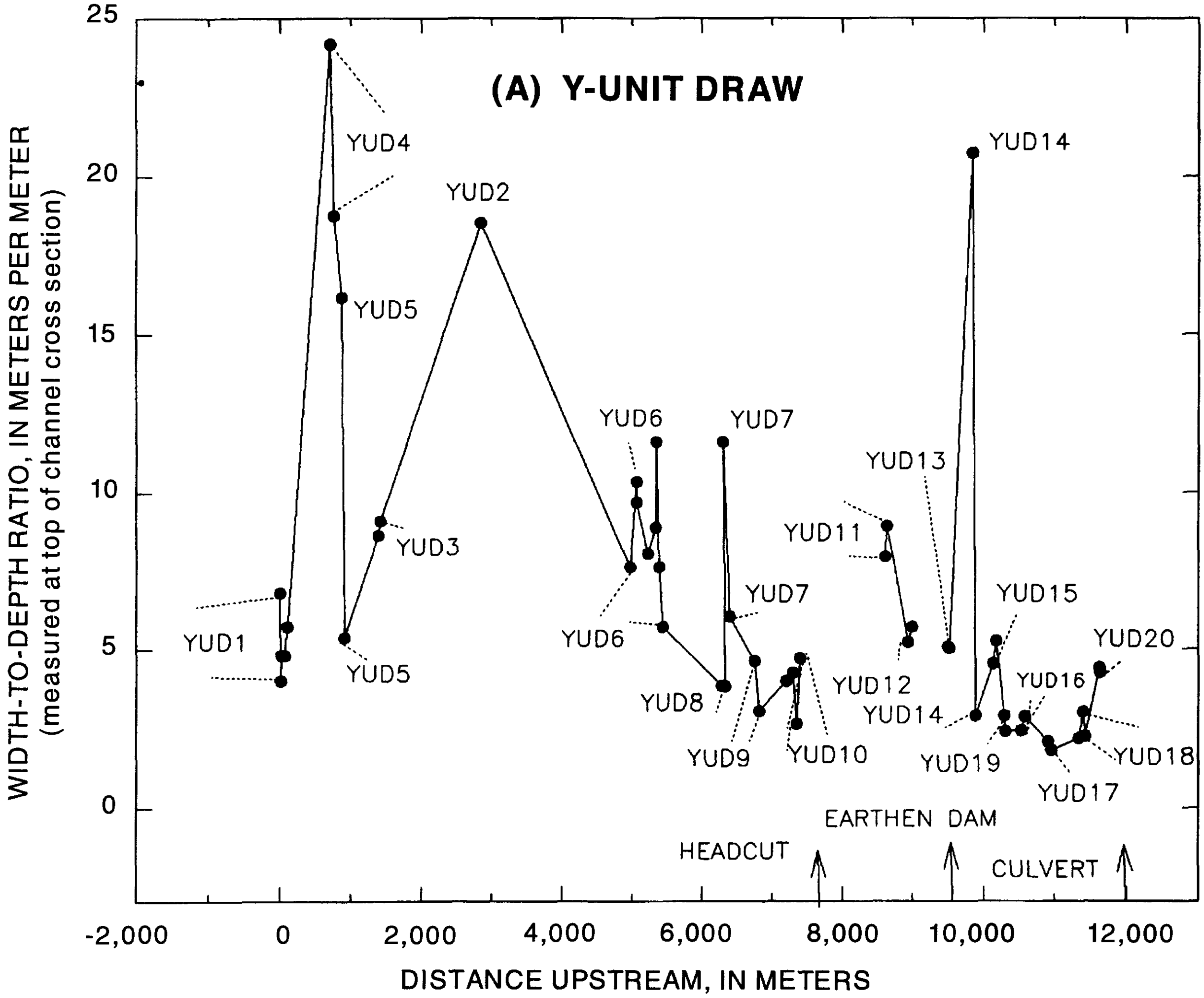


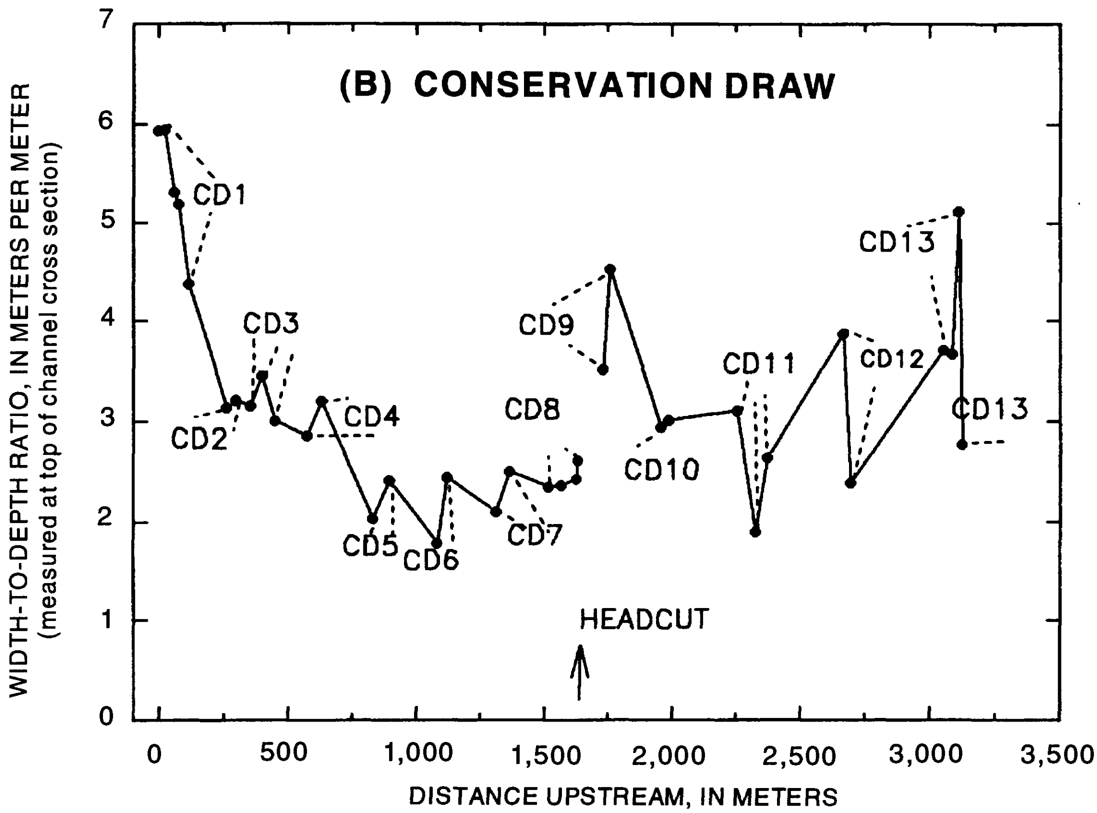
Figure 8.--Distribution of slopes for land-cover types (* indicates slope of trap).



EXPLANATION

YUD5 SURVEYED REACH SHOWN IN FIGURE 4

Figure 9.--Top width-to-depth ratios, surveyed in 1992, along (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries.



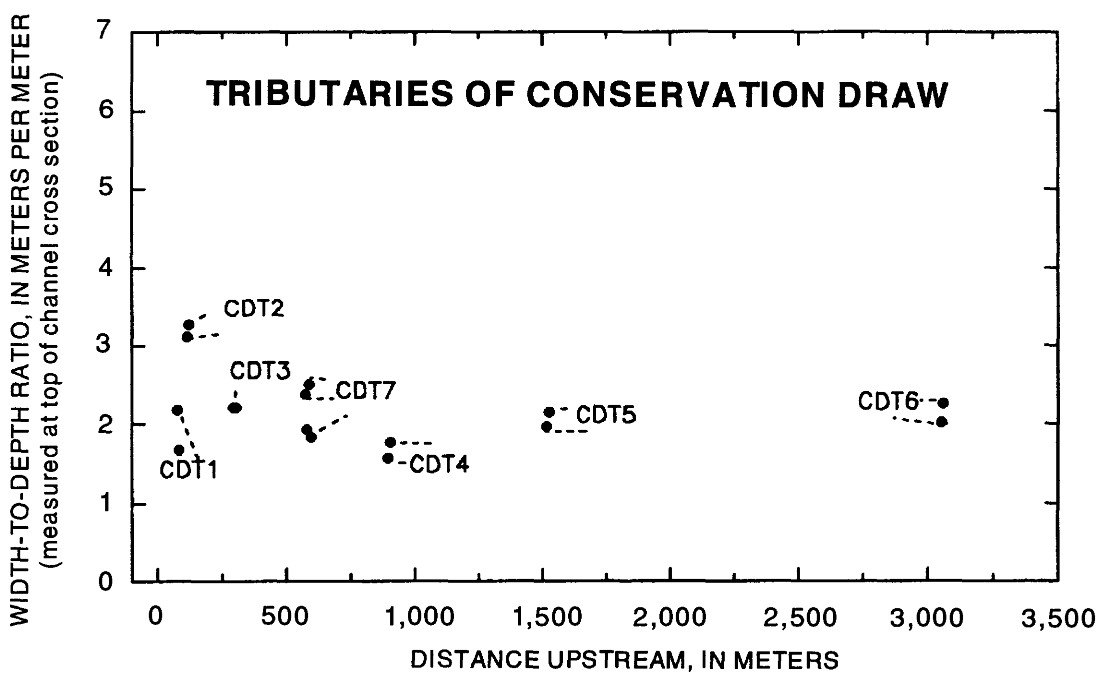
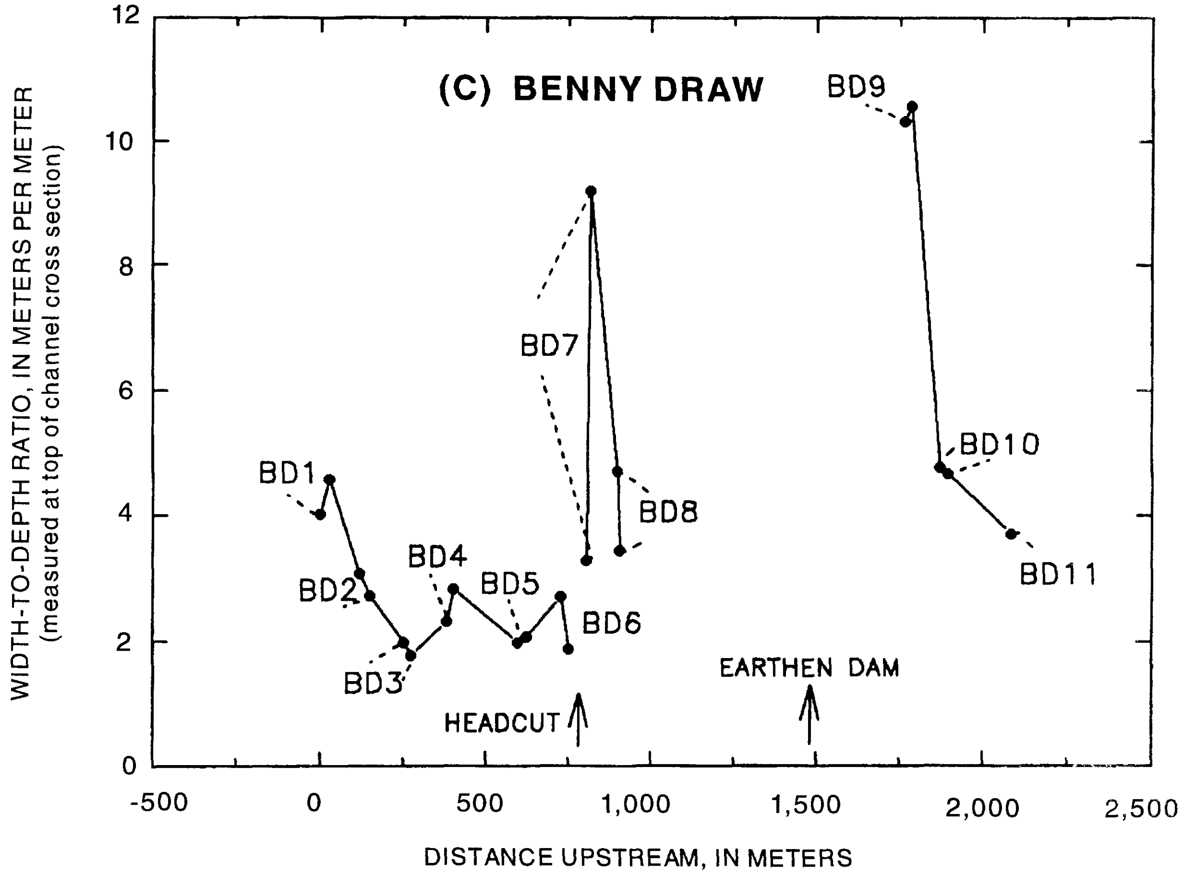


Figure 9.--Top width-to-depth ratios, surveyed in 1992, along (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries--Continued.



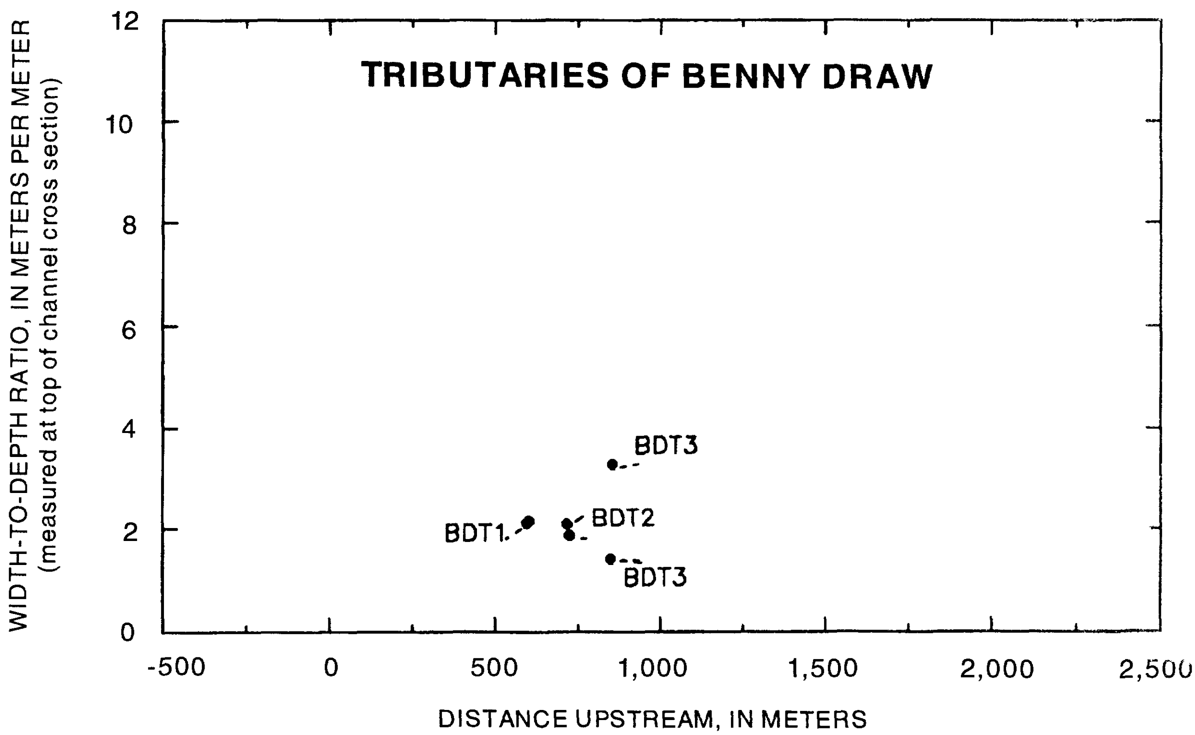
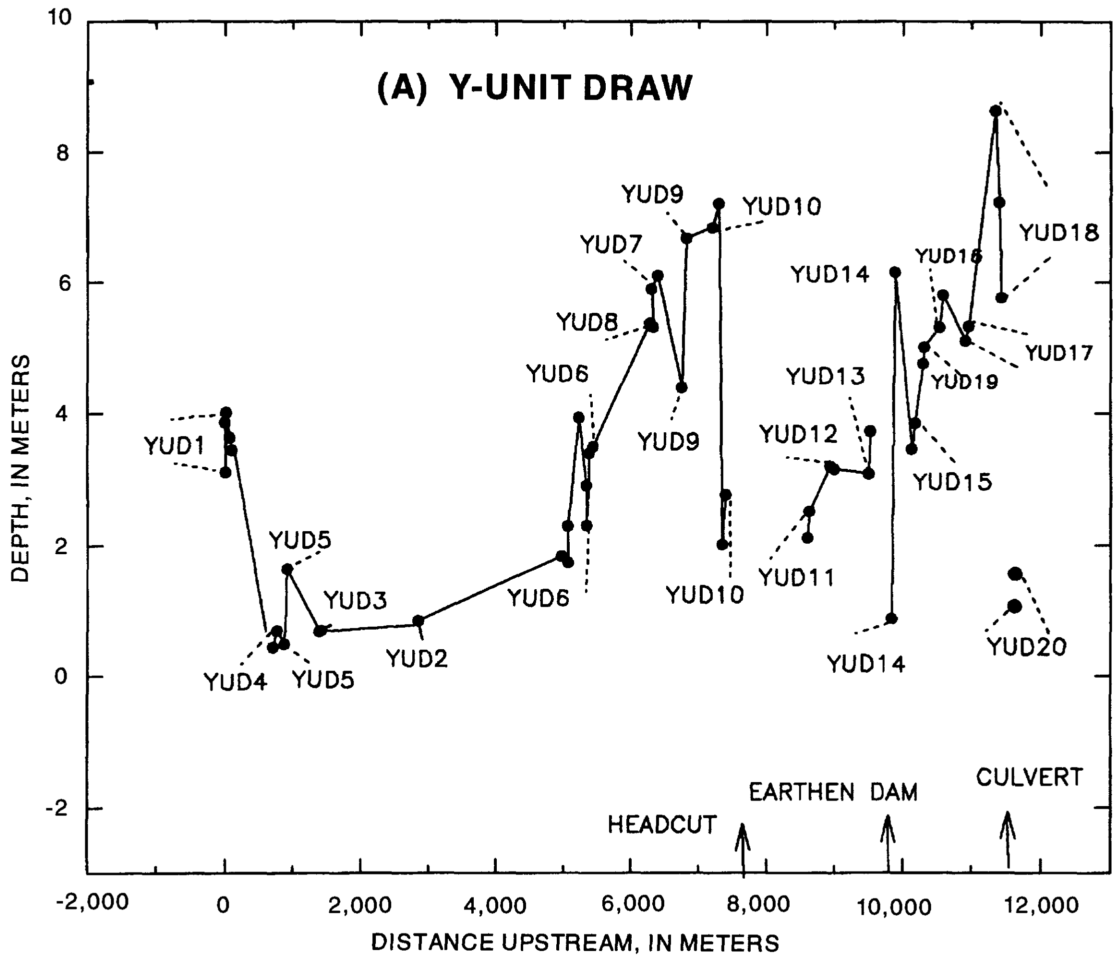


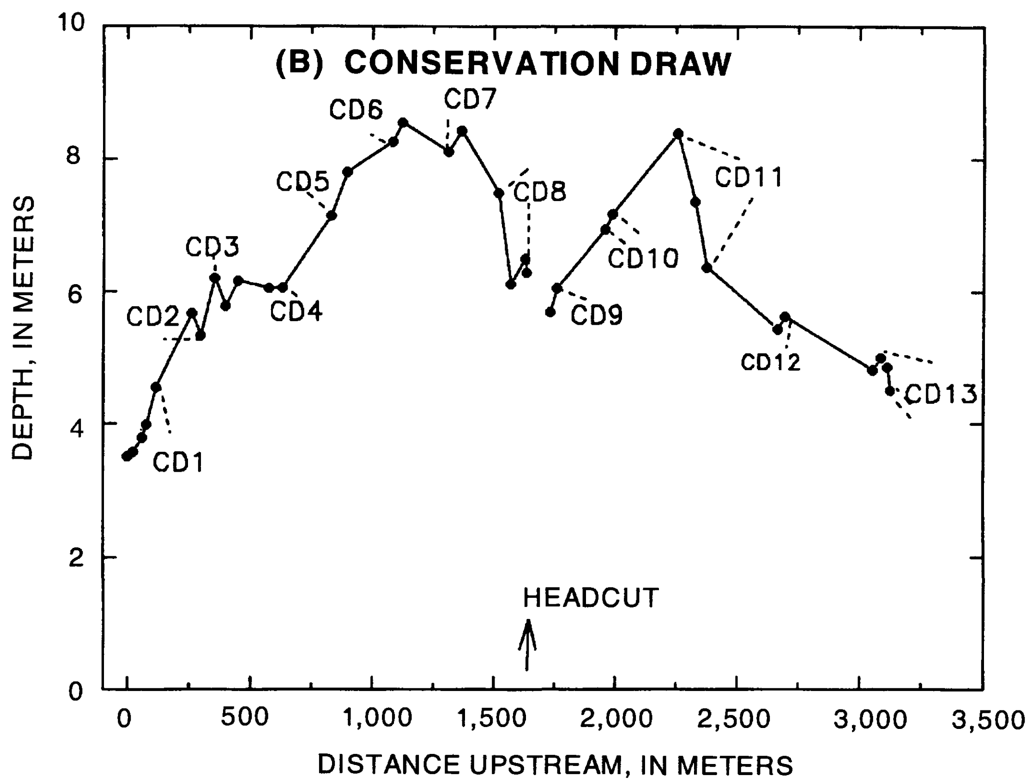
Figure 9.--Top width-to-depth ratios, surveyed in 1992, along (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries--Concluded.



EXPLANATION

YUD5 SURVEYED REACH SHOWN IN FIGURE 4

Figure 10.--Depth, surveyed in 1992, along (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries.



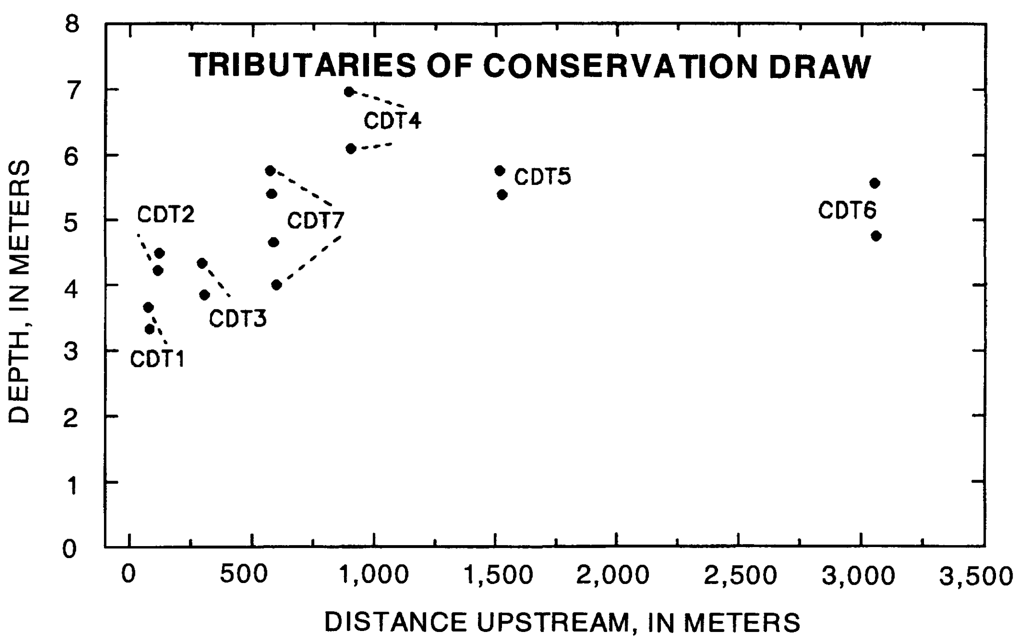
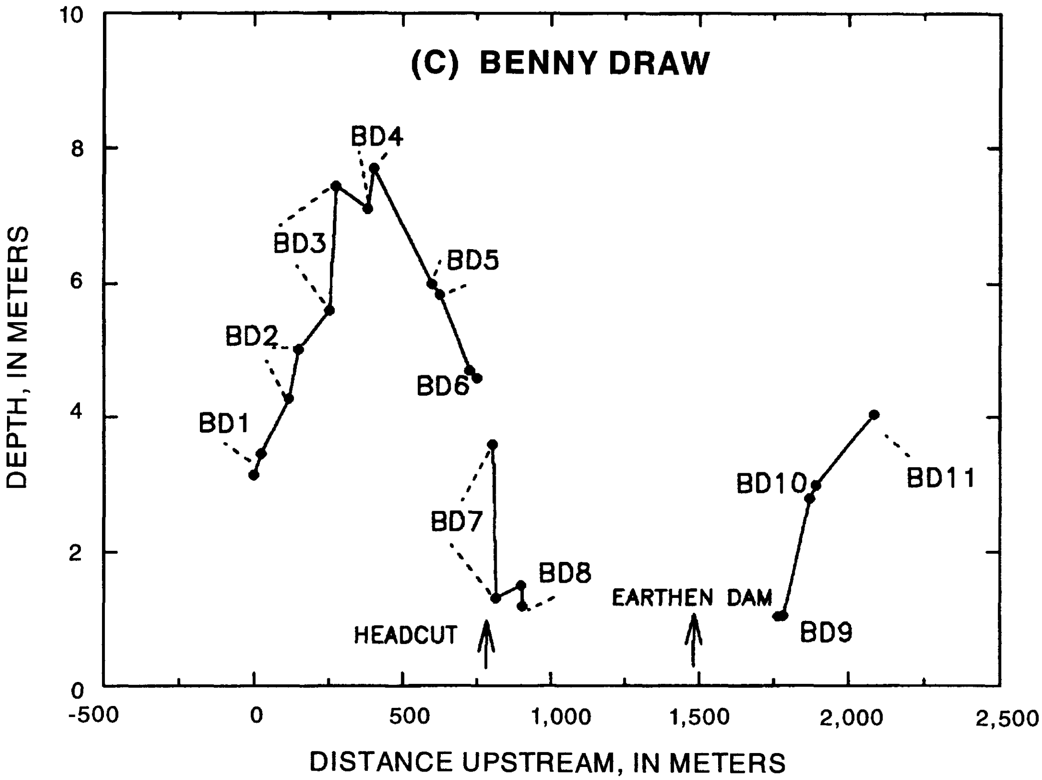


Figure 10.--Depth, surveyed in 1992, along (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries--Continued.



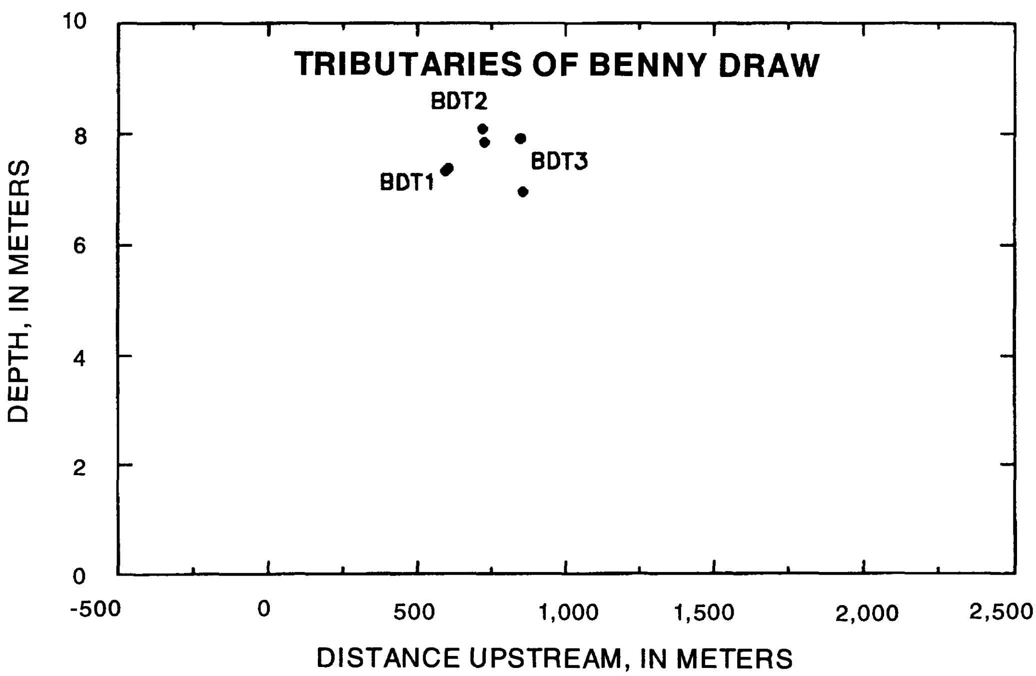


Figure 10.--Depth, surveyed in 1992, along (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries--Concluded.

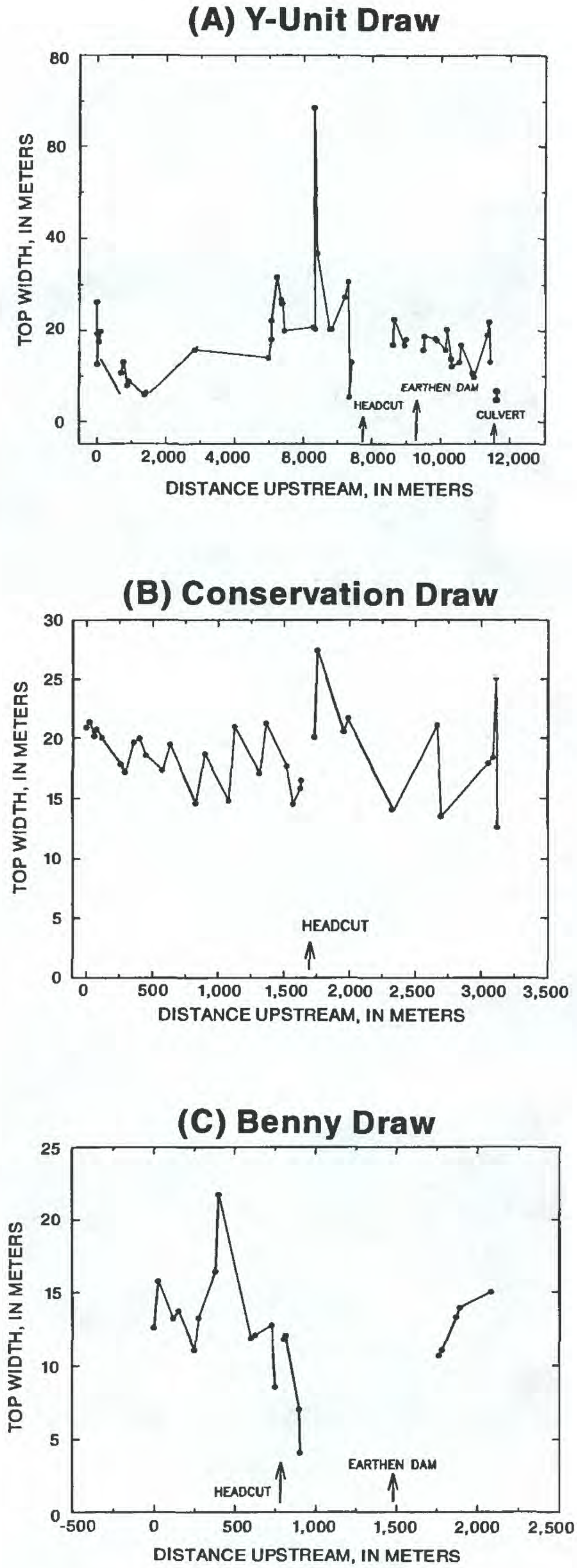


Figure 11.--Top width, surveyed in 1992, along the main channel of (A) Y-Unit Draw, (B) Conservation Draw, and (C) Benny Draw.

Photo: August 1992

(A) CD1

Number of surveyed cross sections = 5
Average top width = 50 meters
Average depth = 3.89 meters
Coefficient of geometry = 0.54

Photo: July 1992

(B) CD5

Number of surveyed cross sections = 2
Average top width = 16.6 meters
Average depth = 7.49 meters
Coefficient of geometry = 0.23

Figure 12.--Changes in the main-channel geometry of Conservation Draw in an upstream direction and in tributary CDT3: (A) CD1, (B) CD5, (C) CD9, (D) CD12, and (E) CDT3.

Photo: July 1992

(C) CD9

Number of surveyed cross sections = 2
Average top width = 23.7 meters
Average depth = 5.88 meters
Coefficient of geometry = 0.27

Photo: October 1992

(D) CD12

Number of surveyed cross sections = 2
Average top width = 17.3 meters
Average depth = 5.54 meters
Coefficient of geometry = 0.25

Figure 12.--Changes in the main-channel geometry of Conservation Draw in an upstream direction and in tributary CDT3: (A) CD1, (B) CD5, (C) CD9, (D) CD12, and (E) CDT3--Continued.

Photo: August 1992

(E) CDT3

Number of surveyed cross sections = 2
Average top width = 9.1 meters
Average depth = 4.10 meters
Coefficient of geometry = 0.09

Figure 12.--Changes in the main-channel geometry of Conservation Draw in an upstream direction and in tributary CDT3: (A) CD1, (B) CD5, (C) CD9, (D) CD12, and (E) CDT3--Concluded.

Fifty-eight percent, 80 percent, and 79 percent of resurveyed cross sections in Y-Unit Draw (fig. 13A), Conservation Draw (fig. 13B), and Benny Draw (fig. 13C), respectively, showed aggradation during 1992-95 (table 4). For all 85 cross sections, 72 percent (n = 61) showed aggradation (fig. 14; table 4). Of these aggraded cross sections, about 59 percent (50) aggraded between 0 and 0.2 m (fig. 14). Aggradation is synonymous with a negative change in depth between surveys. Channel scour is a positive change in depth between surveys and occurred in 27 percent (23) of resurveyed cross sections. Four of these cross sections are in tributaries. Of the 23 cross sections that showed scour, about 57 percent (13) scoured between 0 and 0.1 m. One cross section showed no change.

Of resurveyed cross sections in Y-Unit Draw (31), Conservation Draw (30), and Benny Draw (24), 52, 47, and 62 percent, respectively, showed a decrease in cross-sectional area, meaning that the cross sections have filled in with sediment (table 4). Forty-eight percent of all cross sections showed an increase in cross-sectional area and have eroded. Nine of these eroded cross sections are in tributaries.

The top of the channel widened, between 1992 and 1995, in 67 percent of the resurveyed cross sections (table 4); nine of these cross sections were in tributaries. The bottom of the cross section widened in 44 percent of the resurveyed cross sections (table 4); eight of these cross sections were in tributaries. Widening at the top of the cross section ranged from 0 to 3 m; 78 percent of the cross sections widened from 0 to 0.5 m. Tributary cross sections that widened at the top of the cross section show the lowest top and bottom width-to-depth ratios, 2.3 and 3.9, respectively (table 5). Ninety-three percent of all cross sections that increased in cross-sectional area widened at either the top or bottom of the cross section (table 4).

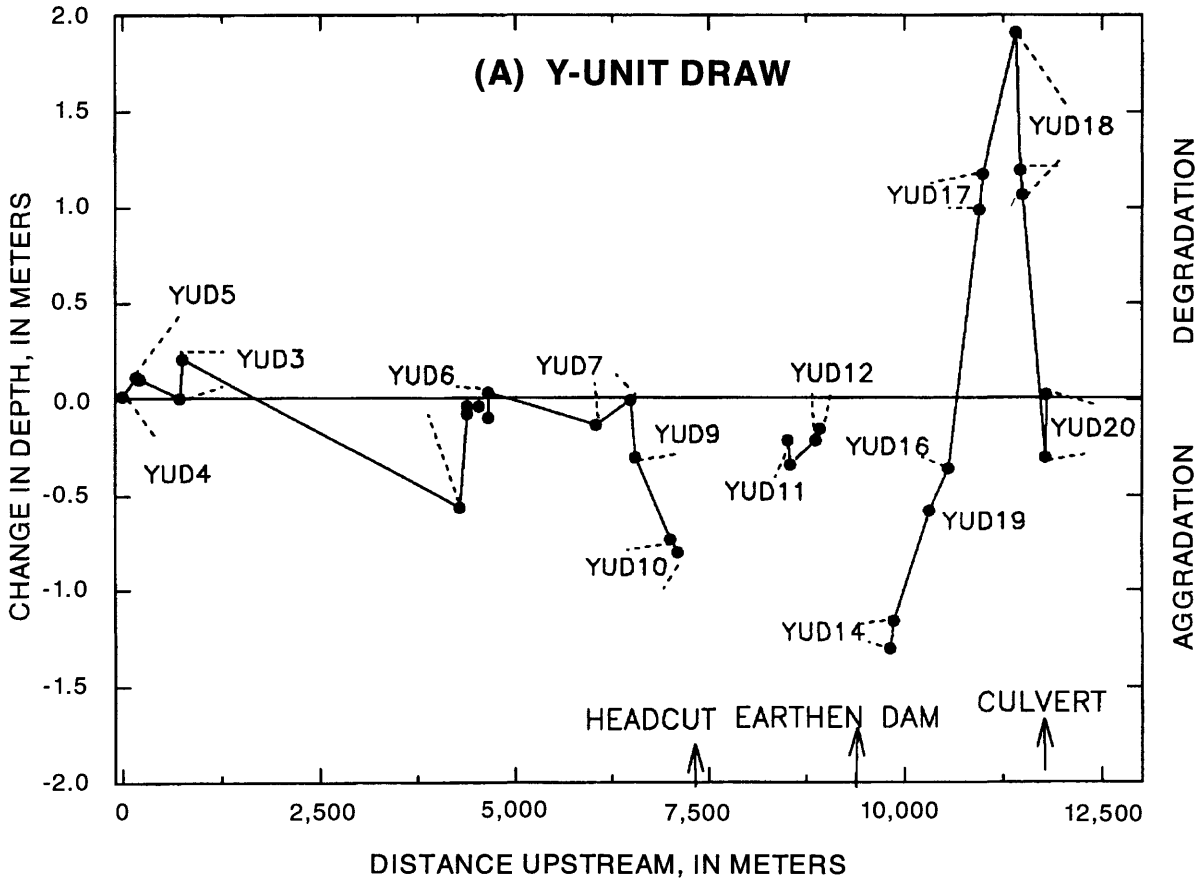
Histograms of top and bottom width-to-depth ratios and mean changes in cross-sectional area indicate that the size class of width-to-depth ratio decreases as the cross-sectional area increases (fig. 15). There was an increase in scour with a decrease in top and bottom width-to-depth ratios for those cross sections that have scoured more than 0.05 m (fig. 16). If an increase in cross-sectional area indicates channel erosion, then narrow, deep channels are more susceptible to erosion. In Oaklimeter Creek, Mississippi, equilibrium was approached when the width-to-depth ratio was approximately 6 (Schumm and others, 1984). Cross sections that have scoured more than 0.05 m and are triangular show higher scour than rectangular cross sections (fig. 16).

An arroyo channel can deepen by the upstream migration of a headcut, and top width-to-depth ratios typically are lower in reaches immediately downstream from the headcut, ranging from 2.29 to 3.63 in the three surveyed subbasins (table 3). Immediately upstream from the headcut the channel has not deepened, and its top width-to-depth ratios tend to be higher, ranging from 3.96 to 8.21 in the three surveyed subbasins (table 3). In Oaklimeter Creek, Mississippi, width-to-depth ratios generally ranged from 4.7 in the channel reach upstream from the headcut to 3.8 in the channel reach immediately downstream from the headcut (Schumm and others, 1984). Width-to-depth ratios reached a maximum of 7.8 12,000 feet (3,658 m) downstream from the headcut.

Width-to-depth ratios of the cross sections also are influenced by human factors. The high top width-to-depth ratios and shallow depths at YUD14 and BD9 (figs. 9 and 10) are due to their locations upstream from an earthen dam. Deposition behind the dam decreases channel depth and increases the top width-to-depth ratio. The great depth of YUD18 is due to its location downstream from a road crossing with a culvert. Flow through the culvert concentrates energy, increases velocities, and accelerates erosion, forming a scour hole downstream that increases channel depth.

The 41 cross sections that increased in cross-sectional area during 1992-95 have an average top width-to-depth ratio of 4.6, which is lower than cross sections that showed fill and have an average top width-to-depth ratio of 4.9. A Mann-Whitney rank sum test showed no statistically significant difference in the median values of the two groups. The average bottom width-to-depth ratio is 4.9 in cross sections that increased in cross-sectional area, which is lower than the 9.0 average bottom width-to-depth ratio in cross sections that filled with sediment. Closer examination of cross sections that increased in cross-sectional area shows that top and bottom width-to-depth ratios are lowest in tributary cross sections (table 5).

Cross sections increased in cross-sectional area by widening or scouring. More cross sections increased in cross-sectional area (41) than scoured (23) because some cross sections that aggraded also increased in cross-sectional area. Twenty-eight, 50, and 47 percent of cross sections in Y-Unit Draw, Conservation Draw, and Benny Draw, respectively, aggraded and increased in cross-sectional area (table 4). Of all cross sections, 43 percent aggraded and increased in cross-sectional area.



EXPLANATION

YUD10 SURVEYED REACH SHOWN IN FIGURE 4

Figure 13.--Changes in depth between 1992 and 1995 for resurveyed cross sections in (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries.

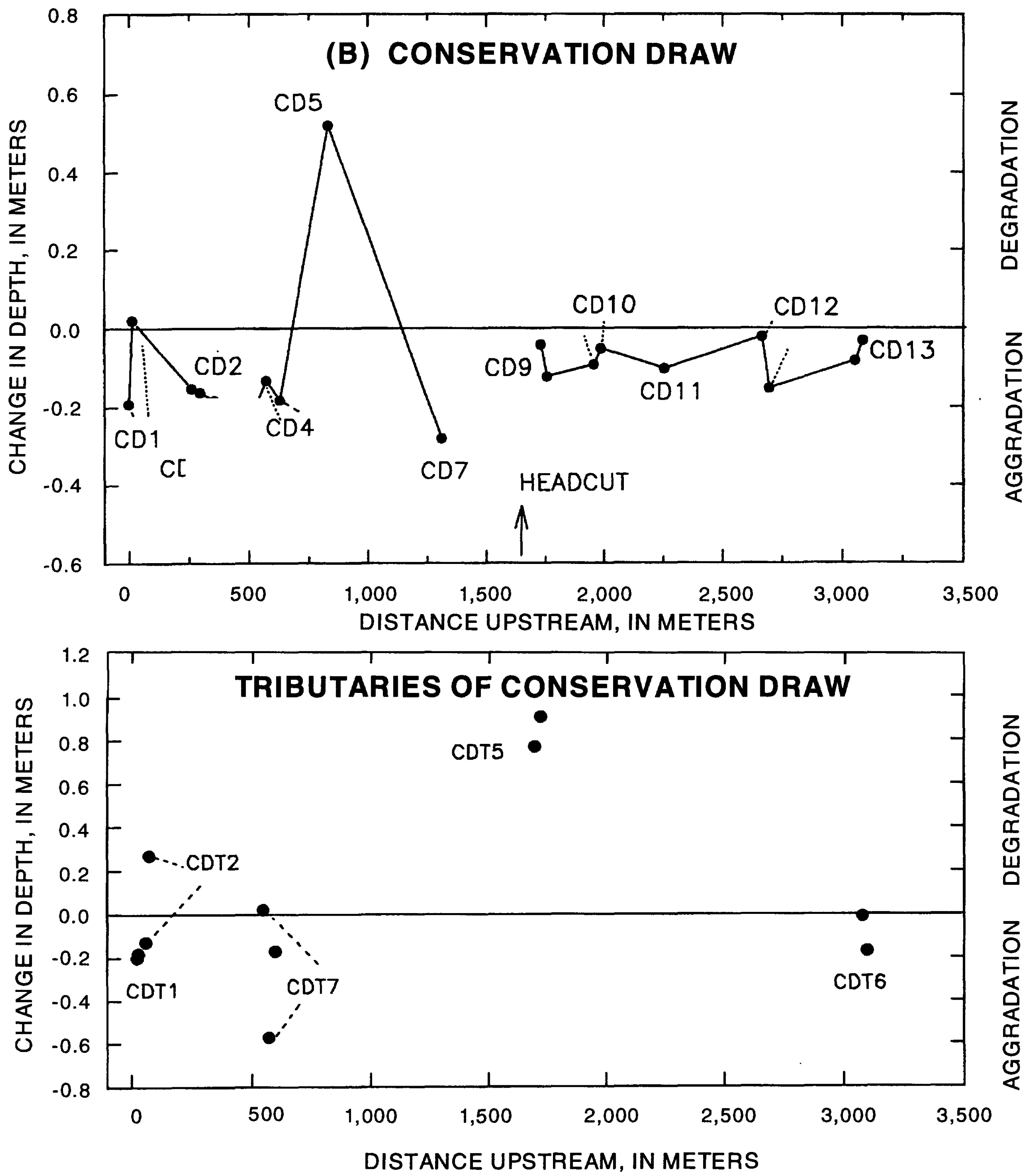
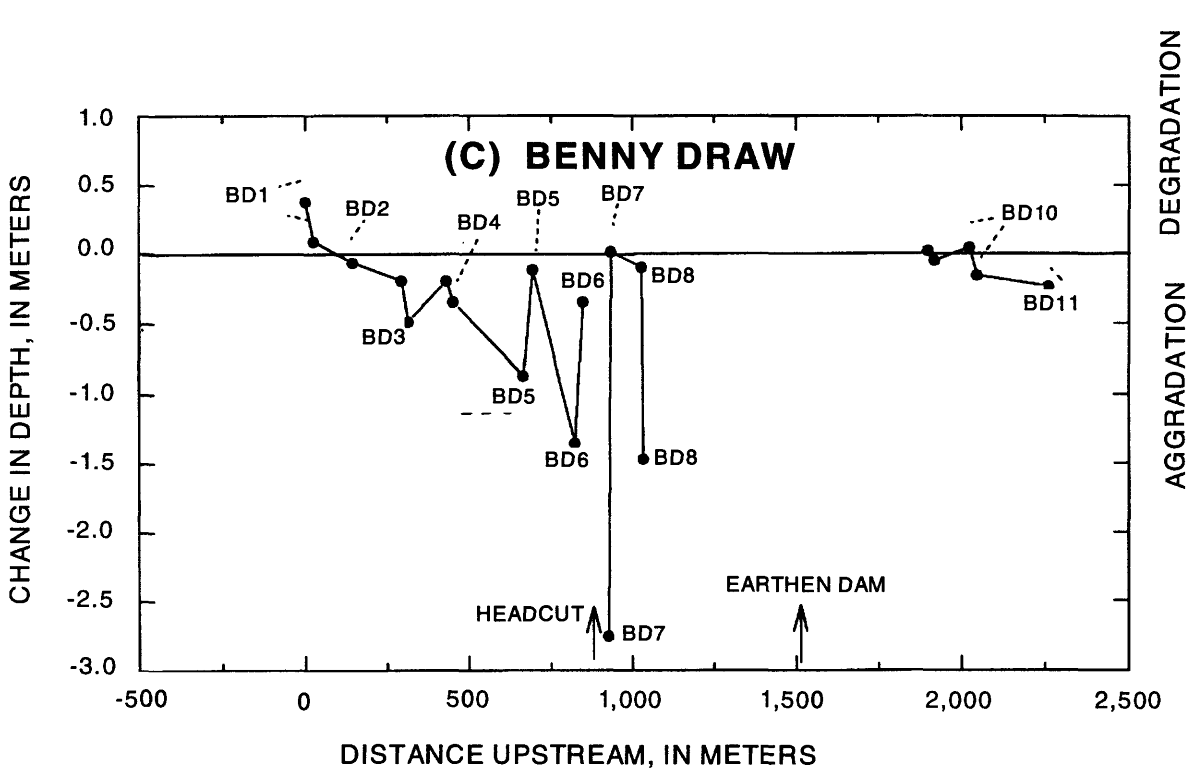


Figure 13.--Changes in depth between 1992 and 1995 for resurveyed cross sections in (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries--Continued.



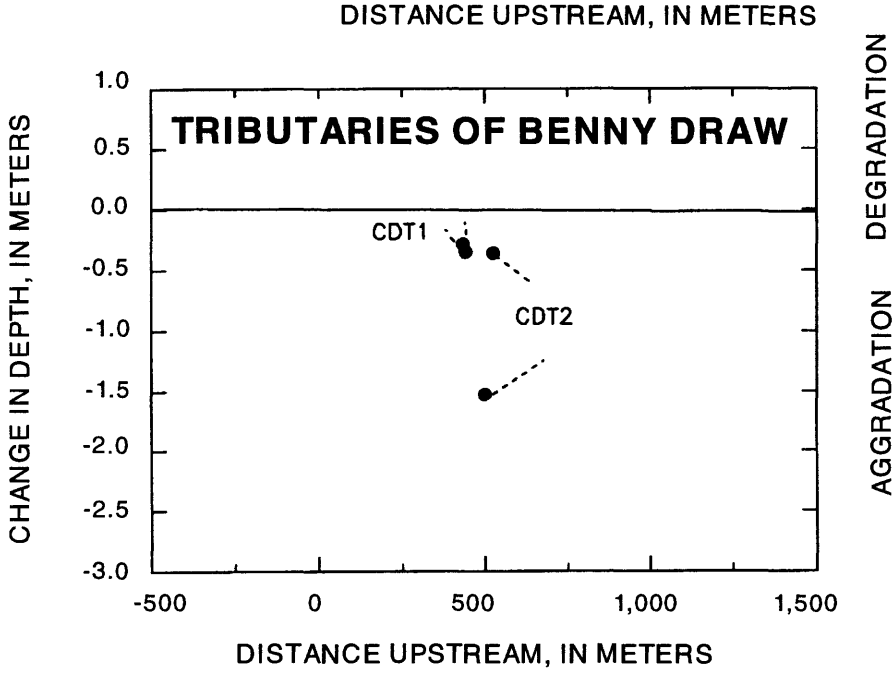


Figure 13.--Changes in depth between 1992 and 1995 for resurveyed cross section in (A) Y-Unit Draw, (B) Conservation Draw and tributaries, and (C) Benny Draw and tributaries--Concluded.

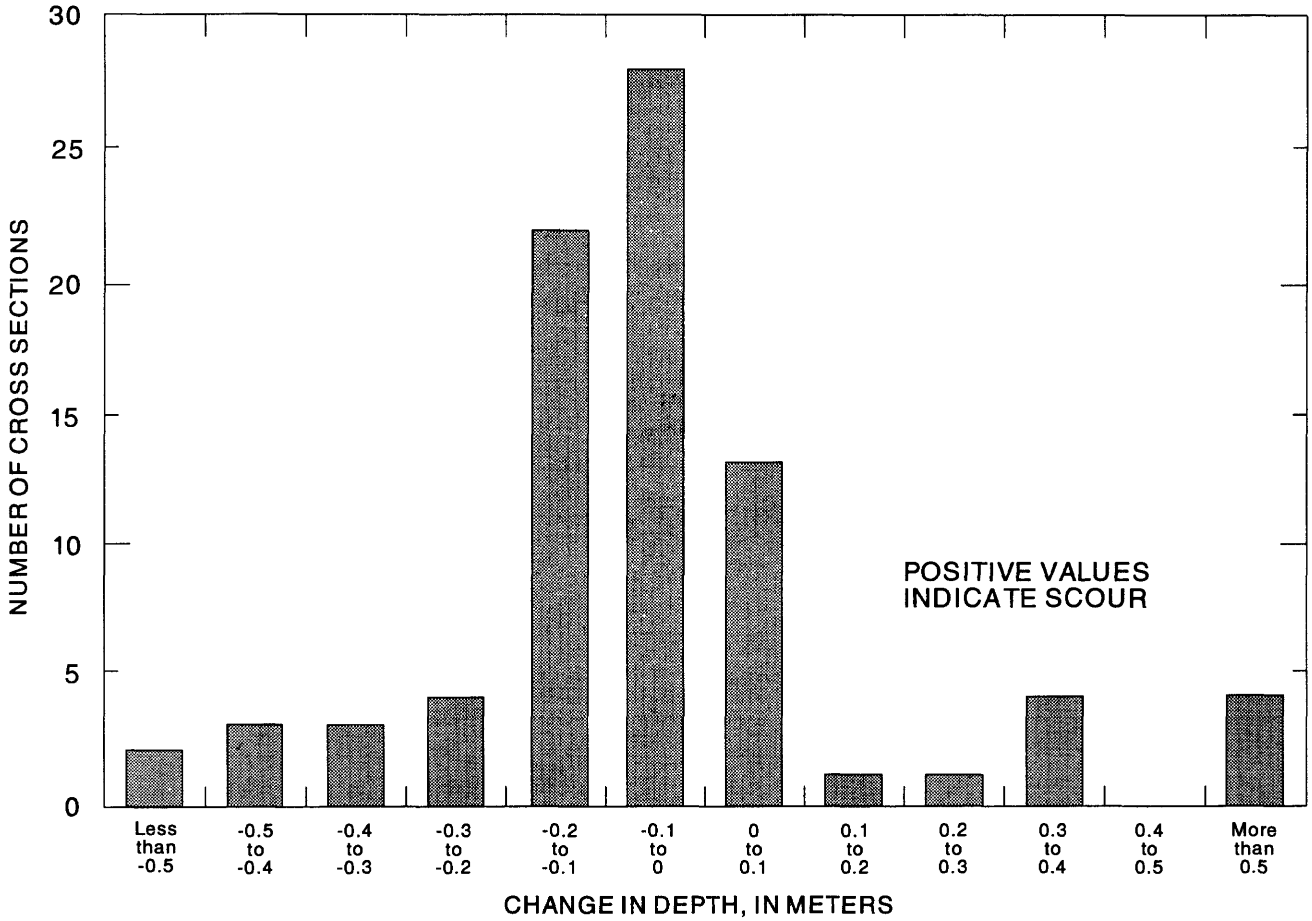


Figure 14.--Distribution of aggradation between 1992 and 1995 for all resurveyed cross sections.

Table 3.--Summary of top width-to-depth ratios, surveyed in 1992, upstream and downstream from headcuts in the three surveyed subbasins of the Rio Nutria watershed

Subbasin and number (fig. 3)	Location	Reach number and number of cross sections	Average top width-to-depth ratio for reach (meters per meter)
Y-Unit Draw - 1	Downstream from headcut	YUD10 - 3	3.63
Y-Unit Draw - 1	Upstream from headcut	YUD11 - 2	8.21
Conservation Draw - 9	Downstream from headcut	CD8 - 3	2.41
Conservation Draw - 9	Upstream from headcut	CD9 - 2	3.96
Benny Draw - 8	Downstream from headcut	BD6 - 2	2.29
Benny Draw - 8	Upstream from headcut	BD7 - 2	6.26

Table 4.--Cross-sectional channel changes in Y-Unit Draw, Conservation Draw, and Benny Draw, 1992-95

Subbasin (fig. 3)	Number of cross sections	Aggradation (percent)	Decrease in cross-sectional area (percent)	Aggradation in addition to:		Increase in cross-sectional area (percent)	Widening at top or bottom of channel cross section and increase in cross-sectional area (percent)
				Increase in top width	Increase in bottom width		
Y-Unit Draw	31	58	52	68	45	28	93
Conservation Draw	30	80	47	59	48	50	94
Benny Draw	24	79	62	71	33	47	90
All cross sections	85	72	52	67	44	43	93

Table 5.--Average changes, 1992-95, in top and bottom width-to-depth ratios for all resurveyed cross sections of (A) increasing cross-sectional area and decreasing cross-sectional area, (B) scour in cross sections and aggrading cross sections, (C) widening at top of channel and nonwidening cross sections, and (D) widening at bottom of channel and nonwidening

Feature	Number of cross sections	Average change in cross-sectional area (square meters)	Average top width-to-depth ratio	Average bottom width-to-depth ratio
A. Change in cross-sectional area				
Cross sections that increased in cross-sectional area (except tributaries)	32	1.65	5.3	5.6
Tributary cross sections that increased in cross-sectional area	9	3.98	2.3	2.4
Cross sections that decreased in cross-sectional area	44	-1.50	4.9	5.5
B. Change in depth of cross section				
Cross sections that scoured (except tributaries)	19	-0.15	6.9	12.4
Tributary cross sections that scoured	4	-0.49	2.4	4.2
Cross sections that aggraded	62	0.15	4.3	7.0
C. Change in width at top of cross section				
Cross sections that increased in top width	48	0.44	5.3	5.3
Tributary cross sections that increased in top width	9	0.30	2.3	3.9
Cross sections that did not increase in top width	28	-0.32	4.7	4.7
D. Change in width at bottom of cross section				
Cross sections that increased in bottom width	29	0.52	5.1	7.2
Tributary cross sections that increased in bottom width	8	0.87	2.2	3.2
Cross sections that did not increase in bottom width	48	-0.54	5.0	9.4

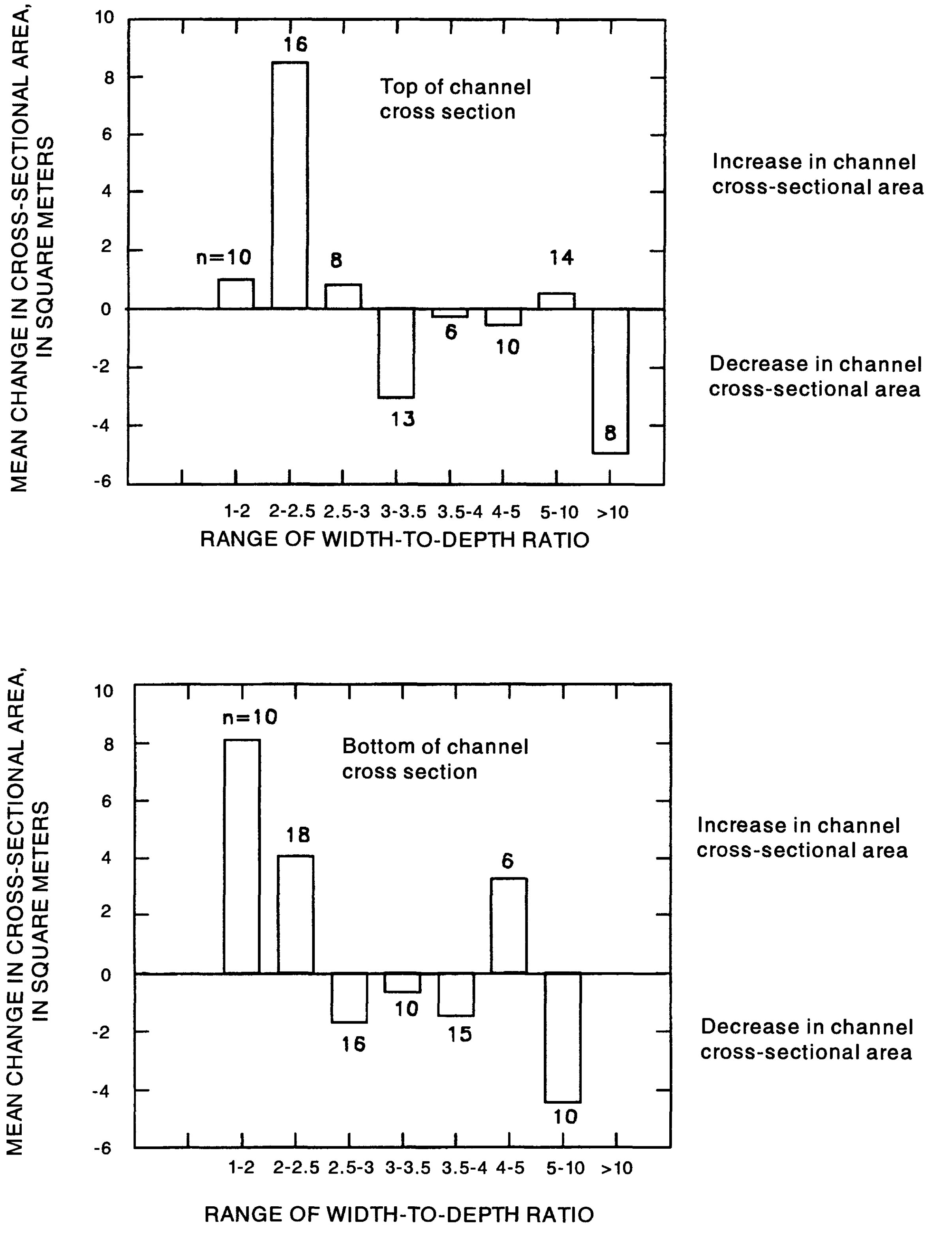
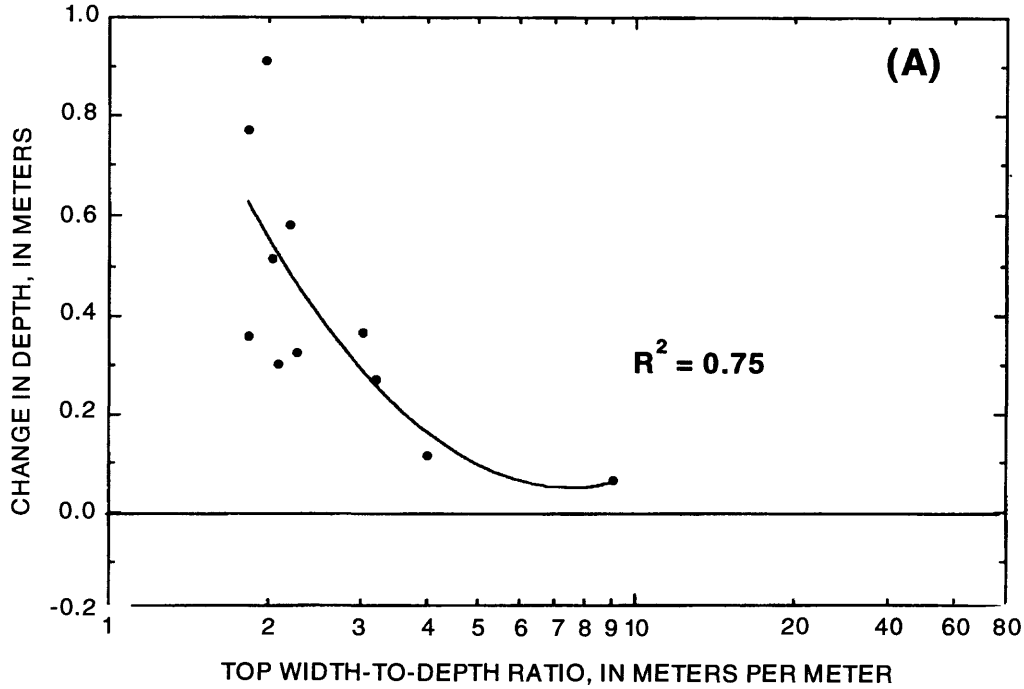


Figure 15.--Relation between width-to-depth ratio and mean change in cross-sectional area between 1992 and 1995 for all resurveyed cross sections.



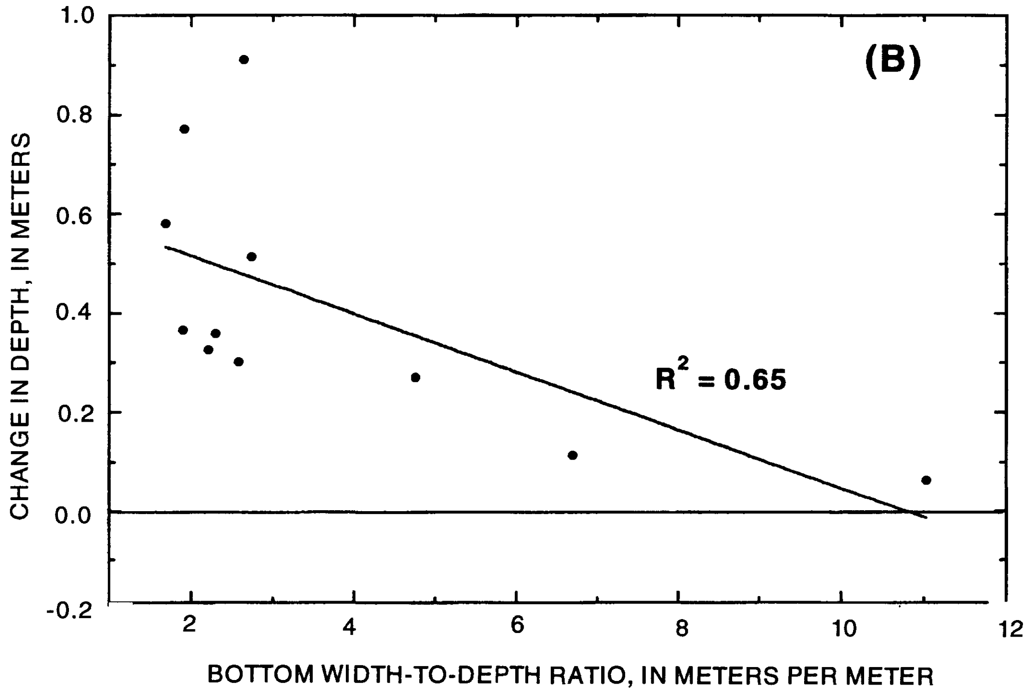


Figure 16.--Relation between scour greater than 0.05 meter between 1992 and 1995 for all resurveyed cross sections and (A) top width-to-depth ratio, (B) bottom width-to-depth ratio, and (C) coefficient of geometry.

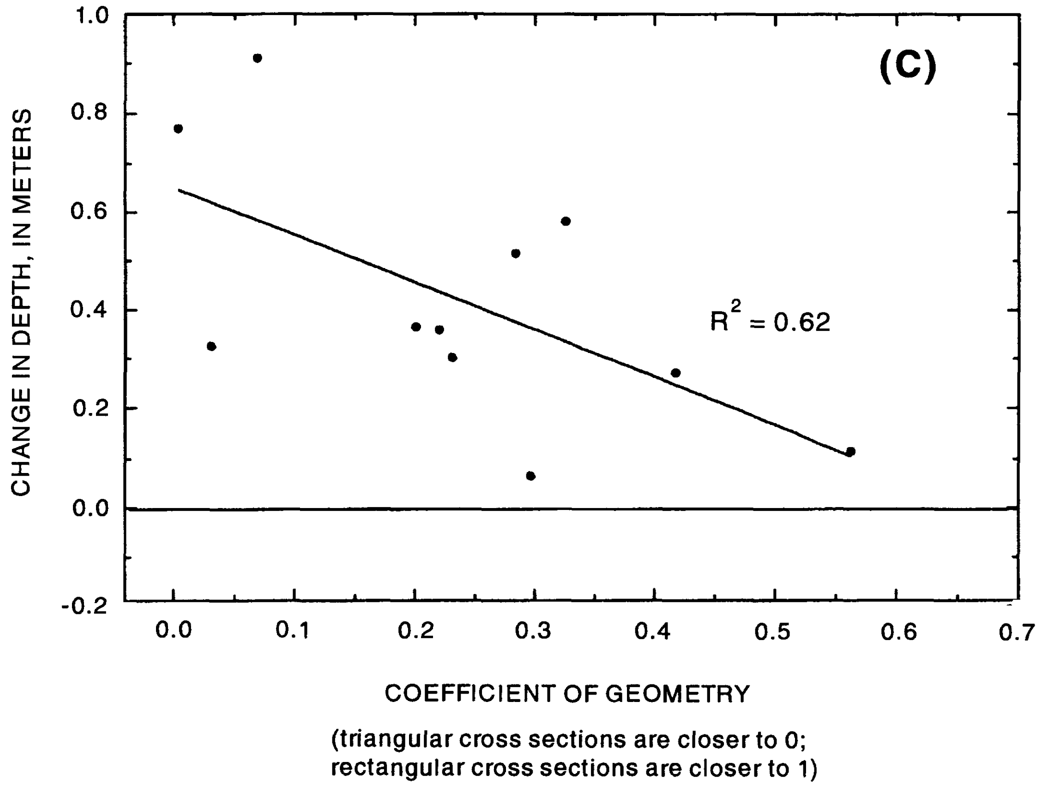


Figure 16.--Relation between scour greater than 0.05 meter between 1992 and 1995 for all resurveyed cross sections and (A) top width-to-depth ratio, (B) bottom width-to-depth ratio, and (C) coefficient of geometry--Concluded.

Channel aggradation may increase cross-sectional area, depending on whether the flows erode into the banks and widen the channel. Ninety-three percent of cross sections that increased in cross-sectional area also widened at either the top or bottom of the cross section. Widening in cross sections is not uniform with depth (table 4). This difference in widening at different depths can occur when the top of the channel is widening as the lower channel is filling in. Sheetwash over the terrace surface as it enters the channel also may widen the top of the channel and increase the cross-sectional area. Channel widening is a more pervasive form of channel erosion than channel scour. Results of the resurveys indicate that a change in cross-sectional area over time is a better indicator of channel erosion than channel scour.

Results of the resurveys indicate that most resurveyed channel cross sections aggraded and most cross sections widened. This may indicate that arroyo evolution for most of the resurveyed cross sections is in stage "c" or higher (fig. 2A). Tributary cross sections show more erosion than main-stem channels (trunk) and may be in stages "b" through "d" (fig. 2A). Several researchers have presented evidence of widespread arroyo aggradation in the Western United States in the 20th century (Leopold and others, 1966; Emmett, 1974; Graf, 1987). Leopold and others concluded, in their study of sediment sources in an ephemeral drainage network, that channels near Santa Fe, New Mexico, were aggrading from 1958 to 1964. Average net aggradation of channels in their study ranged from 0.0009 to 0.030 m/yr. Continued monitoring showed aggradation continuing to 1974 (Leopold, 1976). Reports on channel changes at eight other sites in the Western United States showed either aggradation or equilibrium; none showed degradation (Emmett, 1974). Results from this study support this trend in arroyo aggradation. Because most cross sections in this study are aggrading, a possible decision on gully rehabilitation may be nonintervention. In the Alkali Creek watershed, Colorado, nontreated gullies showed a decrease in soil loss over time (Heede, 1977).

Gully lengths per unit subbasin area increased from 1934 to 1988 in 9 of 12 subbasins for which data are available (fig. 17; table 6). The largest increase in gully length was 5,117 m in Garcia Draw. The largest increase in gully density was 573 m/km^2 in Crow Canyon (fig. 3). For the total area of coverage (285.9 km^2), gully lengths increased 12,062 m from 1934 to 1988 or 0.78 m/km^2/yr. The cause of the larger increase in gully length per subbasin area for the observed subbasins could not be determined; however, the increase probably is related to basin slope, soil type, vegetation type, intensity and duration of rainfall, and land use. Additional data are needed for further analysis.

Lower Nutria, Burnt Timber Canyon, and Three Canyon Draw showed a decrease in total gully length from 1934 to 1988 (fig. 3; table 6). This decrease is due to either structural control or natural processes. The placement of structures in the channels may cause sediment deposition and gully filling. Gully filling with sediment may be due to arroyo evolution, a natural healing and aggradational process (Gellis and others, 1991).

Headcut density in subbasins in the Rio Nutria watershed in 1988 varied from 0.8 to 20.5 headcuts per km^2 (table 6). Headcuts lower the channel base level, which leads to channel incision and rejuvenation of erosion in a basin (Schumm and others, 1984). Subbasins that have relatively higher headcut density may be subject to higher rates of channel erosion.

The length of dirt roads increased in the Rio Nutria watershed (294 km^2) from 97.79 km in 1934 to 307.2 km in 1988 or 13.2 m/km^2/yr. The largest increase in dirt road length of 39.55 km was in the Lower Nutria (fig. 3), an area used extensively for agriculture. The largest increase in dirt roads per unit subbasin area was 1,859 m/km^2 in Three Canyon Draw (fig. 3; table 6). Dirt roads accelerate erosion in two ways: (1) dirt roads convey runoff, which can cause erosion when it enters a channel and (2) the road itself can form a gully.

HILLSLOPE EROSION

A summary of sediment trap data is provided in table 7. Not all traps were operating during the same period. To adjust for this difference in collection periods, the comparison of hillslope erosion at each site included analysis of volume-weighted sediment concentration. The volume-weighted sediment concentration, reported in parts per million, is the ratio of total sediment divided by the total runoff for the period of record.

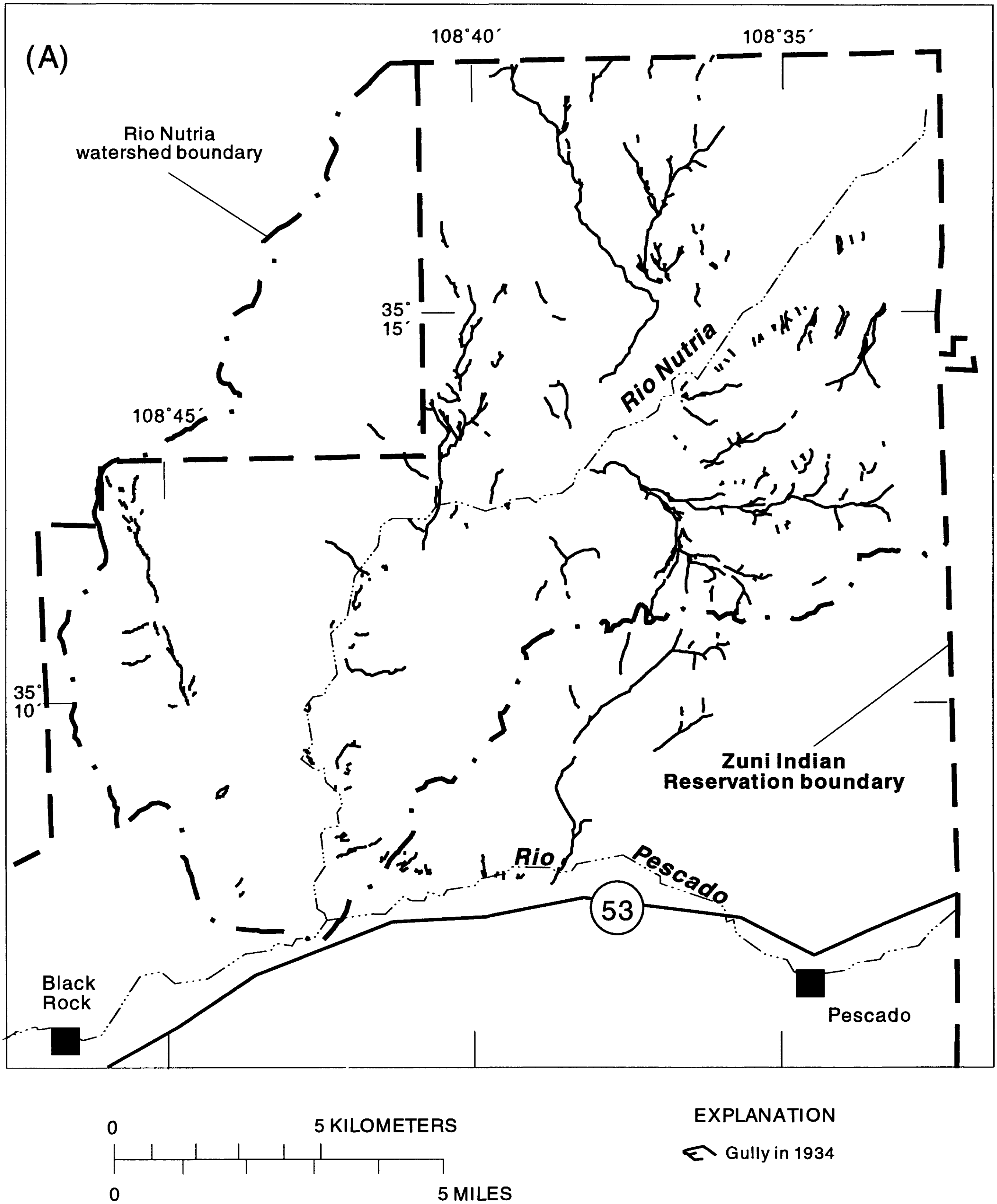


Figure 17.--(A) 1934 gully map of Rio Nutria drawn from 1:28,000-scale aerial photographs and (B) 1988 gully map of Rio Nutria drawn from 1:15,840-scale aerial photographs .

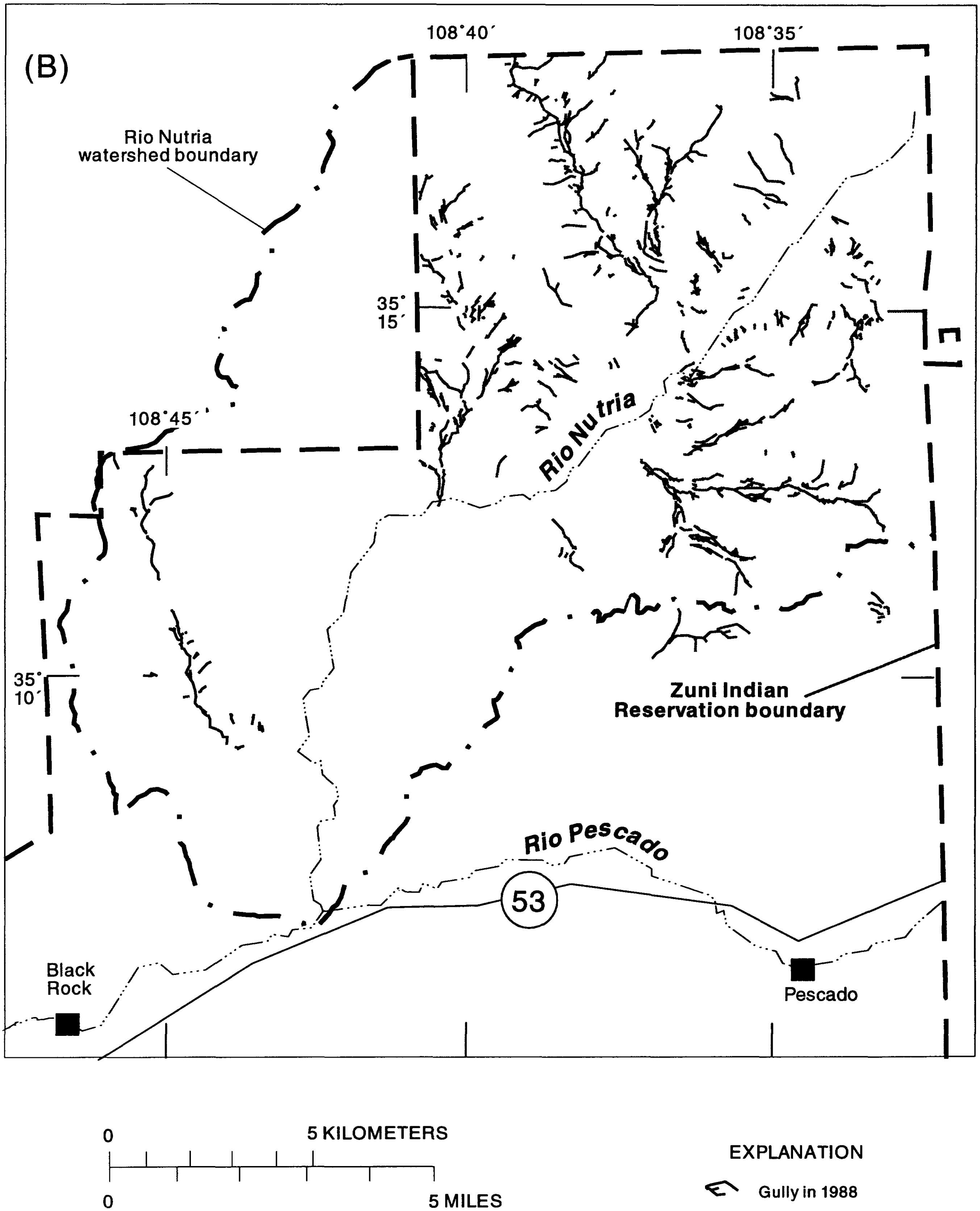


Figure 17.--(A) 1934 gully map of Rio Nutria drawn from 1:28,000-scale aerial photographs and (B) 1988 gully map of Rio Nutria drawn from 1:15,840-scale aerial photographs--Concluded.

Table 6.--Features of selected subbasins

[Location of subbasins shown in figure 3; m/km^2, meters per square kilometer; --, no data]

Features	Y-Unit Draw	Lower Nutria	Coal Mine Canyon Draw	Burnt Timber Canyon	Crow Canyon	Wetlands	Garcia Draw	Benny Draw
Basin area (square kilometers)	24.7	103	26.0	28.7	4.5	39.8	30.1	3.0
Gully length in 1934 (meters)	3,508	5,768	7,410	11,940	1,502	5,174	6,471	1,113
Gully length in 1988 (meters)	3,582	1,751	11,336	11,423	2,578	9,950	11,588	1,323
Change in gully density, 1934-88 (m/km^2)	3	-39	151	-18	239	120	170	70
1988 gully density (m/km^2)	145	17	436	398	573	250	385	441
Headcut density (headcuts/square kilometer)	1.5	0.8	6.0	6.7	6.8	1.0	8.8	17.5
Dirt road length in 1934 (kilometers)	6.79	46.25	2.55	5.48	1.63	22.64	10.36	0
Dirt road length in 1988 (kilometers)	20.6	85.80	30.19	36.82	5.84	61.33	32.12	5.42
Change in dirt road density, 1934-88 (m/km^2)	559	384	1,063	1,092	935	972	723	1,807

Features	Conser-vation Draw	Grass-hopper Canyon Draw	Three Canyon Draw	Blind Canyon Draw	Jimmy Longhose Draw	Box S Canyon	North Burnt Timber Canyon
Basin area (square kilometers)	7.0	3.5	5.4	9.6	3.1	1.8	4.1
Gully length in 1934 (meters)	2,050	--	2,063	777	--	--	1,668
Gully length in 1988 (meters)	2,471	0	1,863	1,910	--	--	1,730
Change in gully density, 1934-88 (m/km^2)	60	--	-37	118	--	--	15
1988 gully density (m/km^2)	353	--	345	199	--	--	422
Headcut density (headcuts/square kilometer)	16.2	3.1	4.6	3.4	5.2	20.5	8.7
Dirt road length in 1934 (kilometers)	0	--	0.74	1.35	--	--	0
Dirt road length in 1988 (kilometers)	2.20	1.58	10.78	8.54	1.60	2.37	1.98
Change in dirt road density, 1934-88 (m/km^2)	314	--	1,859	749	--	--	484

Table 7.--Characteristics of sediment trap sites and summary of data

[ppm, parts per million; %, percent; --, no data]

Land-cover site (fig. 6)	Period of record	Trap number	Number of events sampled	Drainage area (square meters)	Slope (degrees)	Total sediment (grams)	Total runoff (grams)	Total precipitation (millimeters)	Volume-weighted sediment concentration (ppm)
SA-1	8-1-92 to 3-11-94	1	5	7.8	1.8	32.8	42,730	204.0	768
SA-1	8-1-92 to 3-11-94	2	10	11.5	3.7	196	67,670	291.1	2,900
SA-1	8-1-92 to 3-11-94	3	4	19.9	3.8	153	55,610	127.8	2,750
PJ-1	10-23-92 to 10-18-93	1	5	4.1	11.3	13.8	21,900	124.0	630
PJ-1	10-23-92 to 10-18-93	2	7	4.3	14.6	3.2	6,250	88.0	512
PJ-1	10-23-92 to 10-18-93	3	5	2.8	25.2	17.0	5,260	113.8	3,230
PJ-2	6-4-92 to 3-11-94	1	14	15.9	34.7	196	87,650	341.9	2,240
PJ-2	6-4-92 to 3-11-94	2	13	77.3	21.8	421	43,570	339.1	9,660
PJ-2	6-4-92 to 3-11-94	3	17	21.2	34.4	1,630	126,600	426.2	12,900
PO-1	10-23-92 to 3-11-94	1	8	3.7	37.9	457	38,340	193.5	11,900
PO-1	10-23-92 to 3-11-94	2	3	7.9	25.6	2.4	41,700	54.1	57.6
PO-1	10-23-92 to 3-11-94	3	6	3.8	27.9	18.5	7,140	165.4	2,590
PA-1	6-30-92 to 10-18-93	1	9	54.2	17.7	110	31,050	252.0	3,540
PA-1	6-30-92 to 10-18-93	2	12	10.8	16.7	397	72,940	362.7	5,440
PA-1	6-30-92 to 10-18-93	3	12	75.9	8.0	553	138,500	371.6	3,990
PA-2	3-18-93 to 5-26-94	1	3	9.5	3.6	12.6	2,590	74.4	4,860
PA-2	3-18-93 to 5-26-94	2	3	4.7	11.5	38.8	9,450	107.7	4,100
PA-2	3-18-93 to 5-26-94	3	3	3.8	9.4	37.2	3,870	77.7	9,610
PA-3	3-18-93 to 5-26-94	1	4	41.5	5.1	662	25,150	115.8	26,300
PA-3	3-18-93 to 5-26-94	2	3	3.5	4.3	648	21,500	77.7	30,100

Table 7.--Characteristics of sediment trap sites and summary of data--Continued

Land-cover site (fig. 6)	Period of record	Trap number	Number of events sampled	Drainage area (square meters)	Slope (degrees)	Total sediment (grams)	Total runoff (grams)	Total precipitation (millimeters)	Volume-weighted sediment concentration (ppm)
PA-3	3-18-93 to 5-26-94	3	5	5.4	3.6	846	26,650	119.4	31,700
CH-1	10-23-92 to 5-17-94	1	7	27.7	5.2	435	54,340	185.2	8,000
CH-1	10-23-92 to 5-17-94	2	5	3.3	3.4	18.4	3,080	137.9	5,970
CH-1	10-23-92 to 5-17-94	3	10	8.0	11.0	1,360	75,700	242.1	18,000
CH-2	5-4-93 to 5-17-94	1	6	4.7	10.7	227	27,250	173.7	8,330
CH-2	5-4-93 to 5-17-94	2	4	7.4	7.1	2.9	1,840	110.5	1,580
CH-2	5-4-93 to 5-17-94	3	5	10.7	4.3	101	3,000	89.9	33,700

Table 7.--Characteristics of sediment trap sites and summary of data--Concluded

Land-cover site (fig. 6)	Total drainage area of traps (square meters)	Soil texture[1]			Average slope (degrees)	Animal livestock density (animals per hectare)	Total sediment (grams)	Total runoff (grams)	Volume-weighted sediment concentration (ppm)	Sediment yield (grams sediment/grams runoff/square kilometer)
		% sand	% silt	% clay						
SA-1	39.2	69.1	13.6	17.3	3.30	216	382	166,010	2,300	58.7
PJ-1	11.2	--	--	--	16.2	692	34.0	33,410	1,020	90.9
PJ-2	114.4	60.0	22.7	17.3	26.3	414	2,240	257,840	8,690	76.2
PO-1	15.4	74.5	13.7	11.8	29.4	216	478	87,180	5,480	356
PA-1	140.9	83.6	10.0	6.40	12.5	414	1,060	242,480	4,370	31.0
PA-2	18.0	81.8	10.0	8.20	6.90	--	88.6	15,910	5,570	309
PA-3	50.4	80.0	11.8	8.20	11.0	--	2,160	73,300	29,500	583
CH-1	39.0	77.3	10.9	11.8	34.7	692	1,820	133,120	13,700	349
CH-2	22.8	71.8	14.6	13.6	6.60	692	331	32,090	10,300	455

[1]Size classes: clay, less than 0.002 millimeter; silt, 0.002 - 0.05 millimeter; sand, 0.05 - 2.0 millimeters.

Box plots of volume-weighted sediment concentrations for samples collected at each trap show a wide scatter (fig. 18). This scatter may be due to factors such as time of year, rainfall intensity, soil permeability, soil saturation, slope, exposed bedrock, organic litter, and sampling errors, although none of these variables were quantified. The highest volume-weighted sediment concentration--33,700 ppm--was measured at site CH-2, trap 3, a chained area (fig. 19). The next two highest volume-weighted sediment concentrations--31,700 and 30,100 ppm--were measured in grazed pasture at site PA-3, trap 3, and at site PA-3, trap 2, respectively (fig. 19). The two lowest volume-weighted sediment concentrations--57.6 and 512 ppm--were measured at woodland sites at site PO-1, trap 2, and at site PJ-1, trap 2, respectively (fig. 19).

The total sediment and water for each trap was summed, and a volume-weighted sediment concentration for each land-cover type was calculated (fig. 20; table 7). PA-3, a mixed-grass pasture site, and CH-1, a chained piñon and juniper area, had the two highest volume-weighted sediment concentrations of 29,400 and 13,700 ppm, respectively (fig. 20). The lowest volume-weighted sediment concentrations, 1,020 and 2,300 ppm, were measured at an unchained piñon and juniper site (PJ-1) and a sagebrush site (SA-1), respectively. After all traps for a particular land-cover site are summed, the volume-weighted sediment concentrations for each land-cover type, from highest to lowest, are:

Chained piñon and juniper - 13,000 ppm,
Mixed-grass pasture - 9,970 ppm,
Unchained piñon and juniper - 7,810 ppm,
Ponderosa pine - 5,480 ppm, and
Sagebrush - 2,300 ppm.

Erosion typically is reported as sediment yield in tons per square kilometer per year (metric tons/km^2/yr). Because most traps did not operate effectively for a full year this value was not reported. However, sites PJ-2, PA-1, and SA-1 did have collection periods greater than a year, and their annual sediment yields were 11.7, 6.0, and 6.5 metric tons/km^2/yr, respectively. The U.S. Department of Agriculture Soil Conservation Service (SCS) (1974) (now the Natural Resources Conservation Service) reported erosion values ranging from 0.5 to 1.0 acre-foot per square mile per year (238 to 476 m^3/km^2/yr) for the Rio Nutria area. By assuming 100 pounds of soil per cubic foot (1,600 kg/m^3) (Das, 1985), these values correspond to 1,100 to 2,200 tons/mi^2/yr (380 to 760 metric tons/km^2/yr). These SCS values, which are based on the Universal Soil Loss Equation (USLE), range from 32 to 127 times higher than those reported for the sediment trap data. The difference between erosion rates reported in this study and erosion rates reported by the SCS could be related to the short-term nature of the plot studies used in this study or to the USLE methodology used by the SCS. Although the USLE method is based on data collected at a large number of experimental sites, it may be useful only for the areas for which it was developed, which does not include the Zuni Indian Reservation.

Highest sediment concentrations were measured in chained piñon and juniper and mixed-grass pasture areas (fig. 20). These are both areas where vegetation has been reduced. Chaining and removal of piñon and juniper occurred primarily between 1960 and 1980, and many chained areas still contain large portions of bare ground (fig. 7C). Grazing in the pasture areas may also reduce vegetative cover. The highest sediment concentrations in these areas may indicate that soil erosion is related to a decrease in vegetative cover. Lowest erosion values are in woodland areas (ponderosa pine and unchained piñon and juniper) and sagebrush (fig. 20). The woodland areas contain large areas of vegetative cover and leaf litter, which may cause erosion values to be lower than in chained and grazed areas. Slope also could be an important factor influencing erosion. The high volume-weighted sediment concentration for trap 1 at site PO-1 may be due to the high, 37.9-degree slope of that trap (table 7).

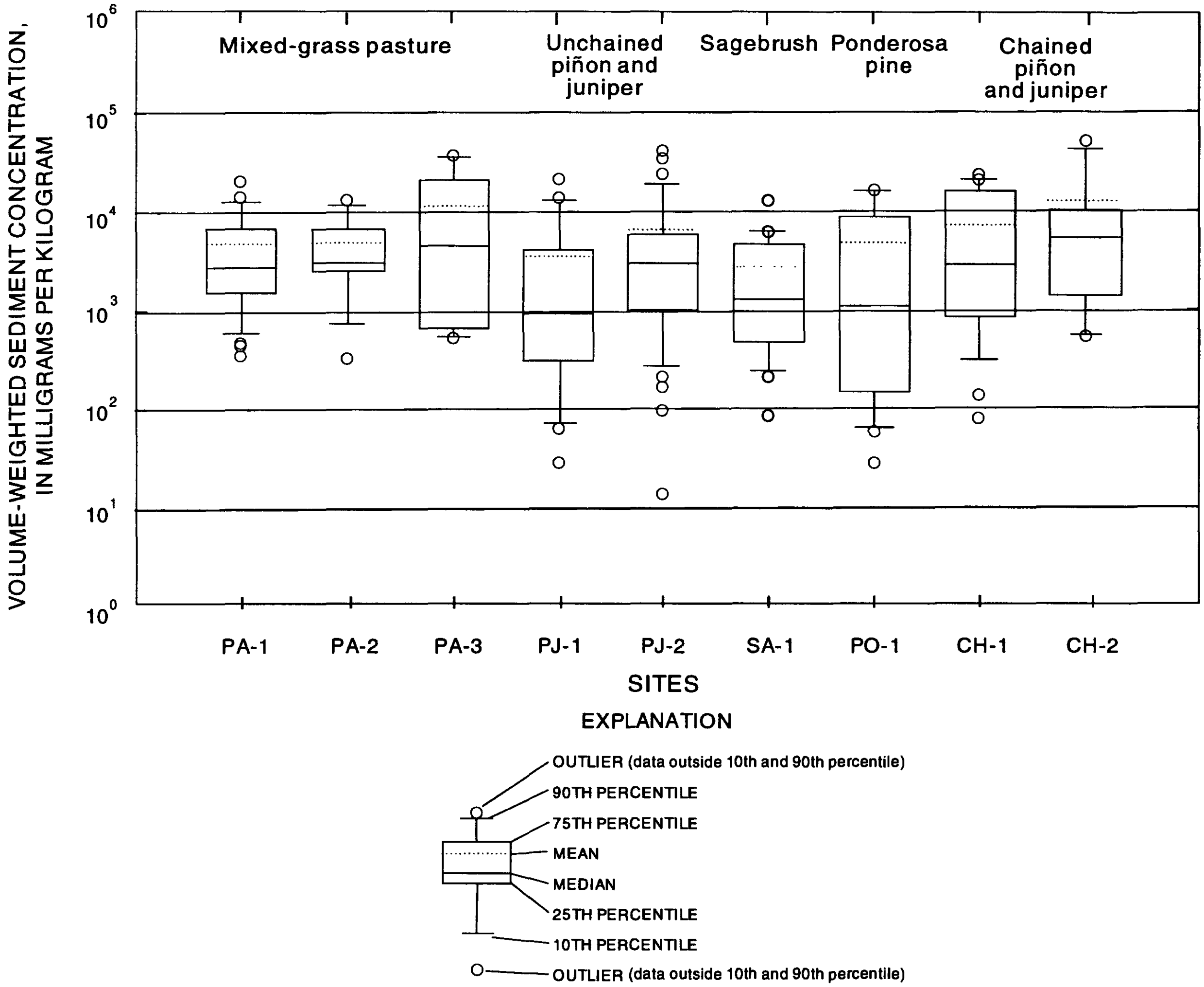


Figure 18.--Sediment concentrations in samples collected from sediment traps, 1992-94.

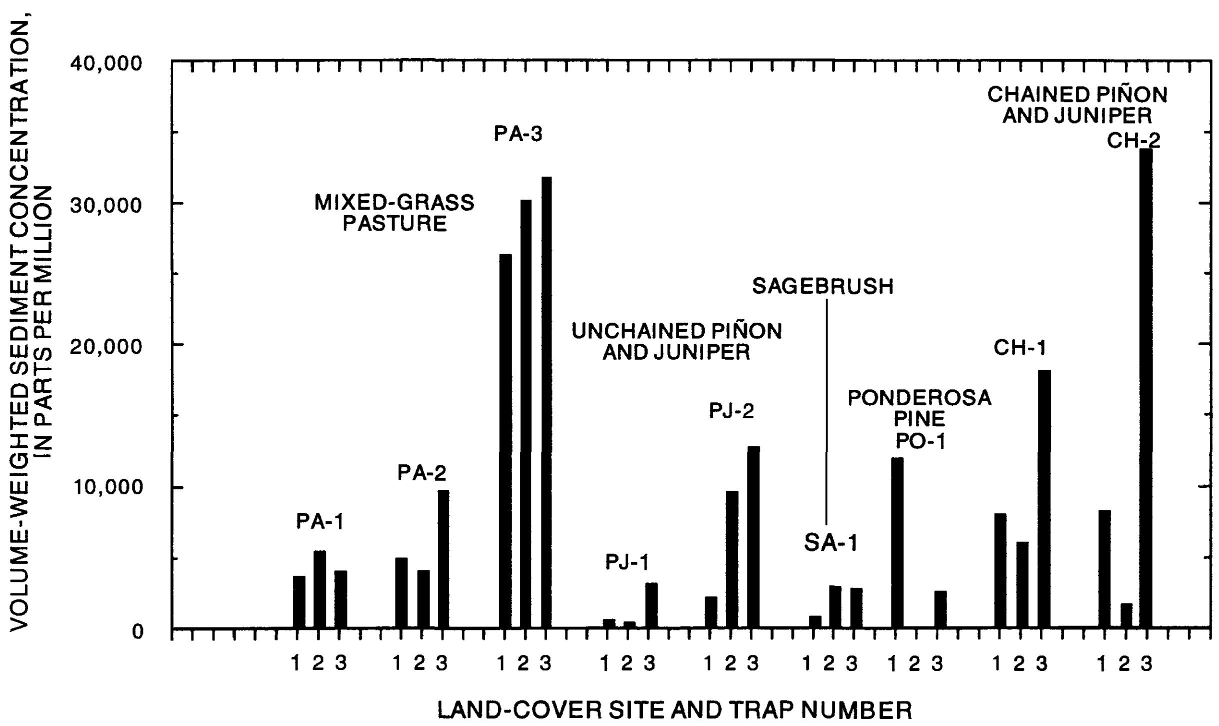


Figure 19.--Volume-weighted sediment concentration for each sediment trap, 1992-94.

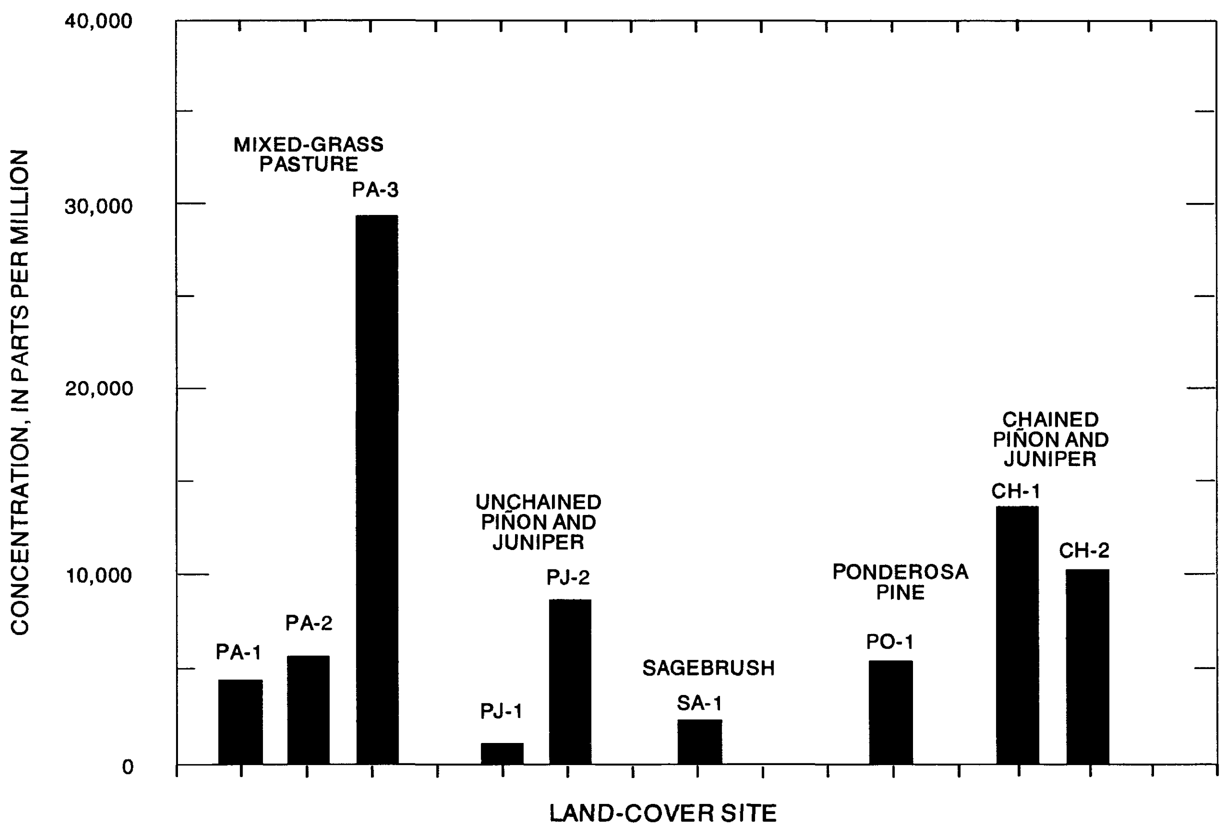


Figure 20.--Volume-weighted sediment concentration for each land-cover type, 1992-94.

SUMMARY

The Zuni Indian Reservation, New Mexico, like many areas of the southwestern United States, has high rates of erosion, ranging from 95 to greater than 1,430 $m^3/km^2/yr$. Erosion on the Zuni Indian Reservation includes channel erosion (arroyo incision), hillslope (sheetwash) erosion, and gullying. The Zuni Land Conservation Act of 1990 mandated that the Zuni Tribe develop a program of watershed rehabilitation. To develop an approach toward watershed rehabilitation, the Zuni Tribe instituted the Zuni Conservation Project. Project staff determined that a pilot watershed, the Rio Nutria watershed, should be studied to provide interpretive data that will assist in watershed-rehabilitation and erosion-control strategies.

In a 3-year USGS study (1992 to 1995), channel changes, gully growth, headcuts, and changes in dirt roads over time were examined to characterize and evaluate channel erosion in the Rio Nutria watershed. Channel cross-sectional changes included width, depth, width-to-depth ratio, area, and geometry. Relative rates of gully growth, headcuts, and changes in dirt roads over time were examined using aerial photographs.

Seventy-two percent of all 85 resurveyed cross sections in three subbasins of the Rio Nutria showed aggradation. For all resurveyed cross sections, 48 percent showed an increase in cross-sectional area and have eroded. Nine of these cross sections are in tributaries. Some channels (43 percent) aggraded and increased in cross-sectional area, due mostly to widening.

The top of the cross section widened in 67 percent of the resurveyed cross sections; nine of these are in tributaries. The bottom of the cross section widened in 44 percent of the resurveyed cross sections; eight of these are in tributaries. Tributary cross sections that widened at the top have the lowest top and bottom width-to-depth ratios. Ninety-three percent of all cross sections that increased in cross-sectional area widened at either the top or bottom of the cross section.

There was an increase in scour with a decrease in top and bottom width-to-depth ratios for those cross sections that have scoured more than 0.05 m. Triangular cross sections that have scoured more than 0.05 m show higher degradation (erosion) than rectangular cross sections.

Headcuts lower the channel base level, which leads to channel incision and rejuvenation of erosion in a basin. Subbasins that have relatively higher headcut density may be subject to higher rates of channel erosion. Gully lengths per unit subbasin area increased from 1934 to 1988 in 9 of 12 subbasins. For the total area of coverage (285.9 km^2) gully lengths increased 12,062 m from 1934 to 1988 or 0.78 $m/km^2/yr$. The length of dirt roads increased in the Rio Nutria watershed (294 km^2) from 97.79 km in 1934 to 307.2 km in 1988 or 13.2 $m/km^2/yr$. Dirt roads convey runoff, which can cause erosion when it enters a channel. Also, a dirt road itself can form a gully.

Channel widening is a more pervasive form of erosion than channel scour on the Zuni Indian Reservation. Results of the resurveys indicate that most resurveyed channel cross sections aggraded and widened. This many indicate that the stage of arroyo evolution for most resurveyed cross sections is stage "c" or higher. Tributary cross sections showed more erosion and may be in stages "b" through "d". Because most cross sections in this study aggraded, a possible decision on gully rehabilitation may be nonintervention.

Five land-cover types--three sites on mixed-grass pasture, two sites on unchained piñon and juniper, one site on sagebrush, one site on ponderosa pine, and two sites on chained piñon and juniper--were each instrumented with three sediment traps to measure hillslope erosion. For particular land-cover types, the volume-weighted sediment concentrations, from highest to lowest, are: chained piñon and juniper - 13,000 ppm; mixed-grass pasture - 9,970 ppm; unchained piñon and juniper - 7,810 ppm; ponderosa pine - 5,480 pm; and sagebrush - 2,300 ppm. Highest sediment concentrations were observed at chained areas and in mixed-grass pasture. Annual yields from sites that were operated for more than a year were 11.7, 6.0, and 6.5 metric $tons/km^2/yr$ at the piñon and juniper site (PJ-2), mixed-grass pasture site (PA-1), and sagebrush site (SA-1), respectively.

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APPENDIX--SELECTED REFERENCES ON EROSION CONTROL AND WATERSHED REHABILITATION

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