



**Prepared in cooperation with the
BUREAU OF LAND MANAGEMENT**

Effects of Roads and Well Pads on Erosion in the Largo Canyon Watershed, New Mexico, 2001–02

Scientific Investigations Report 2006–5039

Effects of Roads and Well Pads on Upland Erosion in the Largo Canyon Watershed, New Mexico, 2001-02

By Anne Marie Matherne

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U.S. Department of the Interior
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Contents

Abstract	1
Introduction	1
Purpose and Scope	4
Previous Investigations	4
Description of the Study Area	4
Climate	4
Resource Use	5
Acknowledgments	5
Approach	5
Dams	5
Roads and Well Pads	15
Precipitation	15
Statistical Analysis	15
Effects of Roads and Well Pads on Upland Erosion	17
Precipitation	17
Erosion Rate	18
Road and Well-Pad Transects	20
Field Observations	26
Roads Parallel to Topographic Contour	26
Roads Across Topographic Contour	38
Well Pads	38
Processes of Upland Erosion	38
Summary	41
References	42

Figures

1-2. Maps showing:	
1. Location of study area, study area features, and climatologic stations.	2
2. Road network in the Largo Canyon watershed and locations of the Harris and Palluche Canyon road- and pad-analysis areas.	3
3A-3F. Orthophotos showing locations of sediment dams:	
3A. In the Harris Canyon area.	6
3B. 1A, 1B, 2A–2D, 3A–3G, and 4A–4C, precipitation gage installed for study, and transects 2PN, 2PS, 3PW, and 3PE, in the Harris Canyon area.	7
3C. 5A, 5B, and 6A–6C, precipitation gage installed for study, and transects 5PE, 5PW, 5RE, 5RW, 6PE, and 6PW, in the Harris Canyon area.	8
3D. 7A–7D and transects 7PN and 7PS, in the Harris Canyon area.	9
3E. 8A–8C and drainage basin for dam 8A in the Harris Canyon area.	10
3F. 9A–9H and corresponding drainage basins in the Harris Canyon area.	11
4A-4C. Orthophotos showing location of:	
4A. Sediment dams, precipitation gage installed for study, and transects in the Palluche Canyon area.	12
4B. Sediment dams 12A and 12B and transects 12 PN and 12PS in the Palluche Canyon area.	13

4C. Sediment dams 13A and 13B and drainage basin for dam 13A in the Palluche Canyon area.	14
5. Bar graph showing total monthly precipitation at the Farmington Agricultural Science Center, Bloomfield 3 SE, Otis, and Lybrook National Weather Service cooperative climatological stations, March 2001–November 2002.	17
6. Box plot showing average erosion rates for drainage areas located below roads, on hillslopes, or below well pads.	19
7-17. Graphs showing:	
7. Land-surface changes for transects (A) 5RE and (B) 5RW in the Harris Canyon area, June 28, 2001–November 20, 2002.	21
8. Land-surface changes for transects (A) 17RL, (B) 17RM, and (C) 17RS in the Palluche Canyon area, June 28, 2001–November 20, 2002.	22
9. Land-surface changes for transects (A) 2PN and (B) 2PS, in the Harris Canyon area, June 28, 2001–November 20, 2002.	23
10. Land-surface changes for transects (A) 5PE and (B) 5PW in the Harris Canyon area, June 28, 2001–November 20, 2002.	24
11. Land-surface changes for transects (A) 6PE and (B) 6PW in the Harris Canyon area, June 28, 2001–November 20, 2002.	25
12. Land-surface changes for transects (A) 16PE and (B) 16PW in the Palluche Canyon area, June 28, 2001–November 20, 2002.	27
13. Land-surface changes for transects (A) 18PN and (B) 18PS in the Palluche Canyon area, June 28, 2001–May 4, 2002.	28
14. Land-surface changes for transects (A) 3PE and (B) 3PW in the Palluche Canyon area, June 28, 2001–November 20, 2002.	29
15. Land-surface changes for transects (A) 7PN and (B) 7PS in the Harris Canyon area, June 28, 2001–November 20, 2002.	30
16. Land-surface changes for transects (A) 12PN and (B) 12PS in the Palluche Canyon area, June 28, 2001–November 20, 2002.	31
17. Land-surface changes for transects (A) 15PE and (B) 15PW in the Palluche Canyon area, June 28, 2001–November 20, 2002. Location of site 15 shown in figure 4A. View is to the west.	32
18-29. Photographs showing:	
18. Truck on road above area of focused bank erosion, Harris Canyon area.	33
19. Sediment dam 9D and weathered shale and siltstone in the drainage contributing area, Harris Canyon area.	33
20. Weathered shale and siltstone in drainage contributing areas of sediment dams 4B and 4C in the Harris Canyon area.	34
21. Areas (indicated by arrows) where headcuts in the upslope road berm near sediment dams 8A and 8C have extended beyond the road berm and up the hillslope, Harris Canyon area.	34
22. Color of sediment on road near sediment dam 1A indicating source of runoff as the weathered shale and siltstone, Harris Canyon area.	35
23. Mud cracks as evidence of ponding and sediment deposition behind the road berm at site 4, in the Harris Canyon area.	36
24. Sediment dam 3F installed at the downslope edge of a road on a pre-existing drainage in the Harris Canyon area.	37
25. Sediment dam 9A overwhelmed by high runoff and partially buried in transported sediment, in the Harris Canyon area.	37
26. Splay deposit, formed from sediment transported along across-contour road and subsequently eroded by runoff, forms the curved cut in berm of parallel-contour road, Harris Canyon area.	39
27. Sediment erosion from upslope pad berm near sediment dam 2C redeposited on the pad, partially burying oil and gas industry equipment, in Harris Canyon area.	39
28. Sediment dam 5A and headcuts eroded into downslope pad berm, Harris Canyon area.	40
29. Author standing in a channel cut by focused runoff near site 12 in the Palluche Canyon area.	40

Tables

1. Sediment yield, drainage area, erosion rate, slope, land use, and landscape position of sediment dams and percentage of sand, silt, and clay of sediment trapped behind sediment dams.	16
2. Mean annual precipitation for the Farmington Agricultural Science Center, Bloomfield 3 SE, Otis, and Lybrook climatologic stations (2001-02) and the National Weather Service 30-year normal precipitation.	18
3. Summary statistics for sediment-dam erosion rate data.	20
4. Number of cuts in upslope and downslope road berms, for road parallel to contour.	36

Conversion Factors and Datum

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m ²)
acre	0.4047	hectare (ha)
square foot (ft ²)	0.09290	square meter (m ²)
square mile (mi ²)	259.0	hectare (ha)
square mile (mi ²)	2.590	square kilometer (km ²)
miles per square mile (mi/mi ²)	0.62150	kilometers per square kilometer (km/km ²)
Flow rate		
cubic foot per year (ft ³ /y)	0.02832	cubic meter per year (m ³ /y)
inch per hour (in/h)	0.0254	meter per hour (m/h)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm²) is restricted to the measurement of small land or water areas.

Effects of Roads and Well Pads on Upland Erosion in the Largo Canyon Watershed, New Mexico, 2001-02

By Anne Marie Matherne

Abstract

Largo Canyon, located in the San Juan Basin of northwestern New Mexico, is one of the longest dry washes in the world. Oil and gas production in the San Juan Basin, which began in the 1940's, required the development of an extensive network of dirt roads to service the oil and gas wells in the Navajo Reservoir area. Presently, there are about eight wells per square mile, and the density of oil and gas wells is expected to increase. Potential environmental effects on landscape stability that may result from the additional roads and well pads have not been documented. In 2001, the U.S. Geological Survey began a study in cooperation with the Bureau of Land Management to evaluate the effects of roads and well pads associated with oil and gas operations on the erosion potential of Bureau of Land Management lands in the Largo Canyon watershed.

The effects of roads and well pads on erosion were quantified by installing sediment dams (dams) and by surveying transects across roads and well pads. Data from 26 dams were used in the analysis. Dams were installed at 43 sites: 21 on hillsides upslope from roads or pads to measure erosion from hillslopes, 11 at the downslope edges of roads to measure erosion from roads, and 11 at the downslope edges of well pads to measure erosion from well pads. Pairs of survey transects were established at nine well pads and two road locations.

Sediment-accumulation data for 26 dams, recorded at 17 measurement intervals, indicate that average erosion rates at the dams significantly correlate to size of the contributing area. The average erosion rate normalized by drainage area was 0.001 foot per year below roads, 0.003 foot per year on hillslopes, and 0.011 foot per year below well pads. Results of a two-sample t-test indicate that there was no significant difference in average erosion rates for dams located on hillslopes and below roads, whereas average erosion rates were significantly greater for dams below well pads than for dams on hillslopes and dams below roads.

The average erosion rates estimated from the data collected during this study most likely represent minimum erosion rates. Sediment-accumulation data for measurement intervals and for dams that were breached during 2002, resulting from the large volume of runoff generated by high-intensity storms, were not used to compute erosion rates. For this reason, the higher range of erosion rates is underrepresented and the results of this

study are biased toward the lower end of the range of erosion rates.

Measurements along road transects generally indicate that sediment is eroded from the top of road berms and redeposited at the base of the berms and may be transported downslope along the road. Measurements along well-pad transects generally indicate that sediment eroded from hillslopes is transported over the surface of the well pad and down the well-pad edges.

Based on field observations, roads aligned parallel to topographic contours facilitate erosional processes in two ways: (1) roads cut across and collect runoff from previously established drainages and (2) roads, where they are cut into hillsides or into the land surface, provide focal points for the initiation of erosion. Roads aligned across topographic contours can serve as conduits to channel runoff but do not constitute a large percentage of the road network.

Introduction

Largo Canyon, located in the San Juan Basin of northwestern New Mexico (fig. 1), is one of the longest dry washes in the world. The canyon cuts into the upper strata of the San Juan Basin, which consist of sandstone and shale of the Nacimiento and San Jose Formations of Tertiary age. Much of the land is under the jurisdiction of the Bureau of Land Management (BLM), and grazing and recreation are part of the multipurpose management strategy for the area. Oil and gas production in the San Juan Basin began in the 1940's. Oil and gas production increased in the early 1970's and the late 1980's, and an extensive network of dirt roads (fig. 2) was constructed to service the wells. Presently, there are approximately eight wells per square mile, and the density of oil and gas wells in the Navajo Reservoir area is expected to increase in the next few decades in a process known as infilling. The BLM Resource Management Plan (Bureau of Land Management, 2003) for the San Juan Basin estimates construction of an additional 805 miles of new roads over the next 20 years. The potential environmental effects on landscape stability that may result from the additional roads and well pads have not been documented. In 2001, the USGS began a study, in cooperation with the BLM to evaluate the effects of upland erosion in the Largo Canyon watershed.

2 Effects of Roads and Well Pads on Upland Erosion in the Largo Canyon Watershed, New Mexico, 2001-02

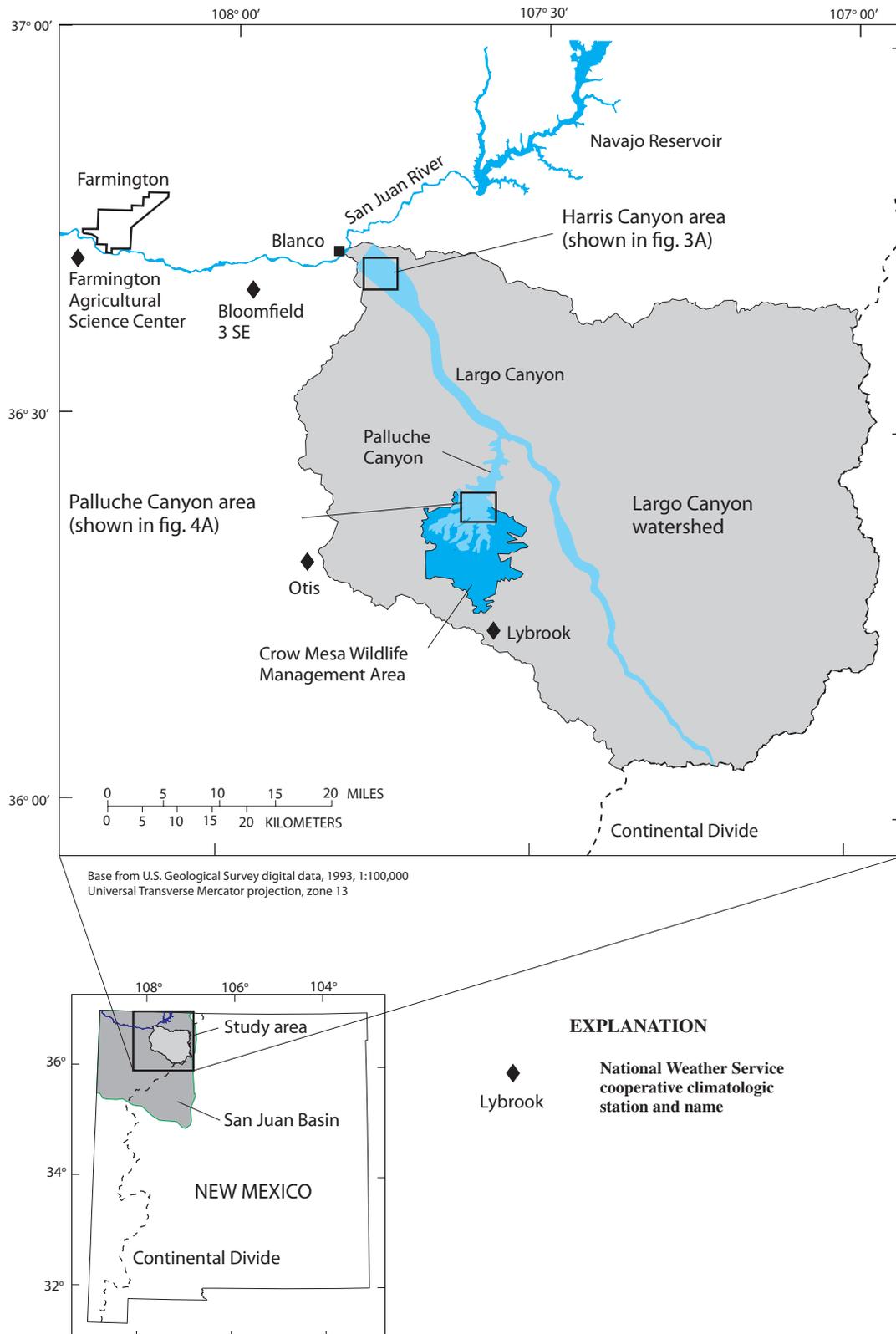
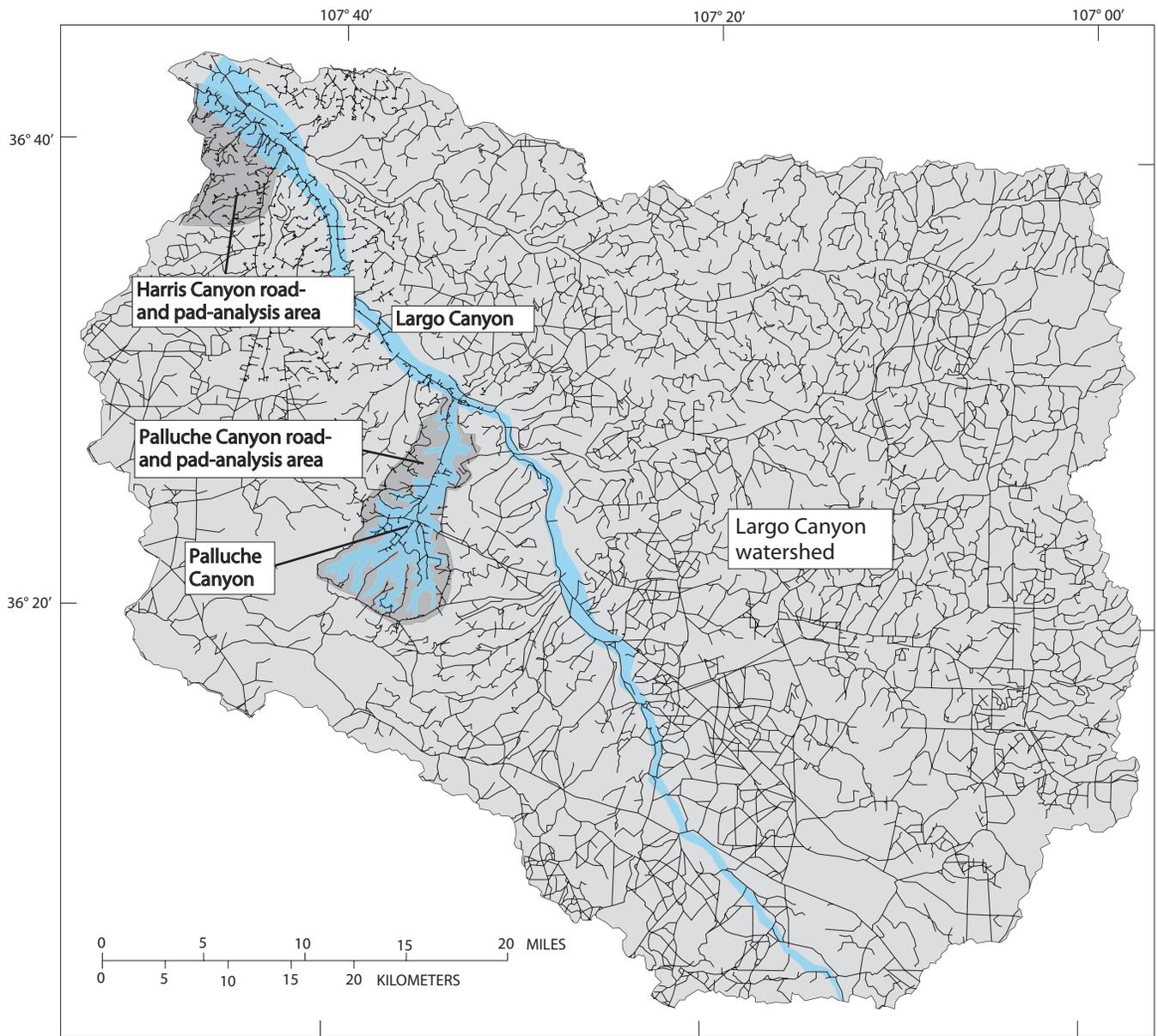


Figure 1. Location of study area, study area features, and climatologic stations.



Base from U.S. Geological Survey digital data, 1993, 1:100,000, and U.S. Geological Survey Digital Orthophoto Quarter Quadrangle, 1997, 1:10,000 Universal Transverse Mercator projection, zone 13

Figure 2. Road network in the Largo Canyon watershed and locations of the Harris and Palluche Canyon road- and pad-analysis areas.

Purpose and Scope

This report presents the results of a 2-year study to evaluate the effects of roads and well pads associated with oil and gas operations on the erosion potential of BLM lands in the Largo Canyon watershed, New Mexico. Data are presented for sediment dams on hillslopes and downslope from roads and well pads and for surveyed transects across roads and well pads. Contributions to erosion from roads and well pads are compared to background contributions from the hillslopes. A conceptual model of the role of roads and well pads in erosion and sediment-transport processes in an arid landscape is presented.

Previous Investigations

Unsealed or unpaved roads and tracks have been found to be the dominant source of surface-runoff generation and transported sediment, on a per unit area basis, on both forested hillslopes and agricultural areas in humid temperate climates (Grayson and others, 1993; Croke and others, 1999; Motha and others, 2003 and 2004) and in the tropics (Dunne and Dietrich, 1982; MacDonald and others, 1997; Anderson and MacDonald, 1998; Ziegler and others, 2000). The infiltration capacity of compacted road surfaces is low compared to surrounding areas, and the potential for generation of surface runoff and transported sediment from roads is correspondingly higher. Although unpaved roads are the primary source areas for erosion-producing surface runoff in response to frequent, low-magnitude rainfall, surface runoff from agricultural and forested areas becomes a more substantial source of runoff for high-intensity or long-duration events because of the larger areal extent of forested and agricultural areas compared to road surfaces (Ziegler and Giambelluca, 1997). In both Australia (Motha and others, 2003) and Thailand (Ziegler and others, 2000), sediment available for erosion and transport by surface runoff was correlated to the disturbance of surface sediment by vehicular traffic. On steep, forested hillslopes in Idaho (Megahan, 1974; Megahan and others, 2001), erosion and sediment transport are focused on the road prism (cutbank, road surface, and fill bank). Erosion rates are highest in the first year after road construction and decline thereafter.

At the hillslope scale (less than 33 ft²), Reid and others (1999) reported substantial sediment transport and deposition on arid hillslopes of piñon-juniper woodland in New Mexico. At this scale, large quantities of sediment are eroded, transported, then redeposited on the hillslope primarily by runoff from large convective summer storms.

In addition to serving as a source of surface runoff and sediment erosion, a road also can serve as a collecting and focusing mechanism for surface runoff. On steep, forested hillslopes with thin soil, shallow subsurface ground-water flow can discharge and become surface runoff at road cuts (Megahan, 1983). Surface runoff collected by roads from many small inlets can leave the road at a single, much larger outlet at a discharge that often is sufficient to initiate or enlarge a downslope channel

(Montgomery, 1994). In a survey of the Petroglyph National Monument, New Mexico, Gellis (1996) determined that 60 percent of the gullies mapped received runoff from dirt roads. Hill-slope erosion associated with roads was found to be mainly associated with sites where the roadbed intersected an established drainage channel on the hillslope (Mosley, 1980; Best and others, 1995).

Description of the Study Area

Largo Canyon (fig. 1) drains an area of 1,700 mi². The head of Largo Canyon is on the western slope of the Continental Divide, trends northwest for about 68 mi, and empties into the San Juan River at Blanco, New Mexico. The regional topography is composed of mesas dissected by deep, narrow canyons and arroyos. The elevation difference between the mesa top and the bottom of Largo Canyon is about 800 ft near the mouth of the canyon. Largo Canyon, a broad flat valley that is about 2 mi wide near the mouth of the canyon and about 0.5 mi wide in the upper canyon, is bounded by steep, rock-faced canyon walls. An alluvial channel, eroded by an ephemeral stream, is generally incised 10 to 20 ft into the valley floor. Side canyons commonly are deep and narrow with near-vertical canyon walls. Accumulations of talus and colluvial sediment at the base of the canyon walls form steep slopes that transition into flat-bottomed arroyos within the canyons. The elevation difference between the mesa top and the bottom of the side canyons is generally 300 to 400 ft.

The landscape morphology and erosion potential of the Largo Canyon watershed are tied to its underlying geology. Rocks of the Nacimiento Formation of Tertiary age are exposed at the surface in approximately the lower 20 percent of the canyon's length (Dane and Bachman, 1965). Rocks exposed at the surface in most of the watershed are primarily those of the San Jose Formation of Tertiary age. Rocks of the Nacimiento and San Jose Formations are composed primarily of interbedded layers of sandstone and shale of predominantly non-marine origin (Brister and Hoffman, 2002). The cliff-forming sandstones are more resistant than the shales but eventually weather into their composite sands; the shale is highly erodible and weathers into silts and clays, resulting in a highly erodible landscape and an abundant sediment supply. Variations in erodibility of the different rocks result in a typically southwestern landscape dominated by sandstone-capped mesas and deep and narrow canyons and arroyos.

The predominant vegetation is sagebrush and grasses with a more restricted piñon-juniper association (Dick-Peddie, 1993). Riparian vegetation, including cottonwood and willow, was observed along Largo Canyon and some of the larger tributary canyons.

Climate

The climate of the Largo Canyon watershed is arid, averaging less than 10 in. of rainfall annually. As is typical of the

southwestern United States monsoonal weather pattern, most annual precipitation falls from July through September; October through June is relatively dry. Snow, as measured at the Bloomfield 3 SE climatologic station (fig. 1), generally falls from December to mid-February and averages less than one-half inch in depth (Western Region Climate Center, 2004).

Resource Use

BLM land in the Largo Canyon watershed is classified as multiple use and is open to recreational and agricultural use. Numerous archaeological sites are scattered throughout the canyon. Winter grazing is permitted throughout most of the watershed, but cattle were excluded from portions of the Crow Mesa Wildlife Management Area (fig. 1) 7 years prior to the beginning of this study (1994). The Crow Mesa area is one of reduced oil and gas activity, compared with other parts of the watershed, due to a relative lack of underlying oil and gas reserves (Dale Wirth, BLM, oral commun., 2001).

Acknowledgments

Dale Wirth of the Farmington BLM Field Office provided support and background information on the study area, which has contributed to the understanding of this project.

Approach

Variables considered for examining the effects of roads and well pads on upland erosion in the Largo Canyon watershed included geology and soil type, position of the road or well pad within the landscape, and the presence or absence of cattle grazing. Because roads and well pads were in active use, it was necessary to develop methods of measurement that did not impede traffic. Based on field reconnaissance, study sites were selected to represent a range of observed variables. The objective was to instrument enough study sites so a representative data set could be collected. Most study sites were located within the Harris Canyon area where cattle are allowed to graze and in the Paluche Canyon area within the ungrazed portion of the Crow Mesa Wildlife Management Area (fig. 1). Sites included dams, transects, or a combination of both (figs. 3-4). Dams were used to collect runoff from a defined drainage area, and transects were used to measure change in elevation across well pads or roads. For a given site, a dam is designated by the site number followed by a single letter. A transect is designated by the site number, R or P (road or well pad), and N, S, E, or W (north, south, east, or west), reflecting relative position of the site transects on the landscape.

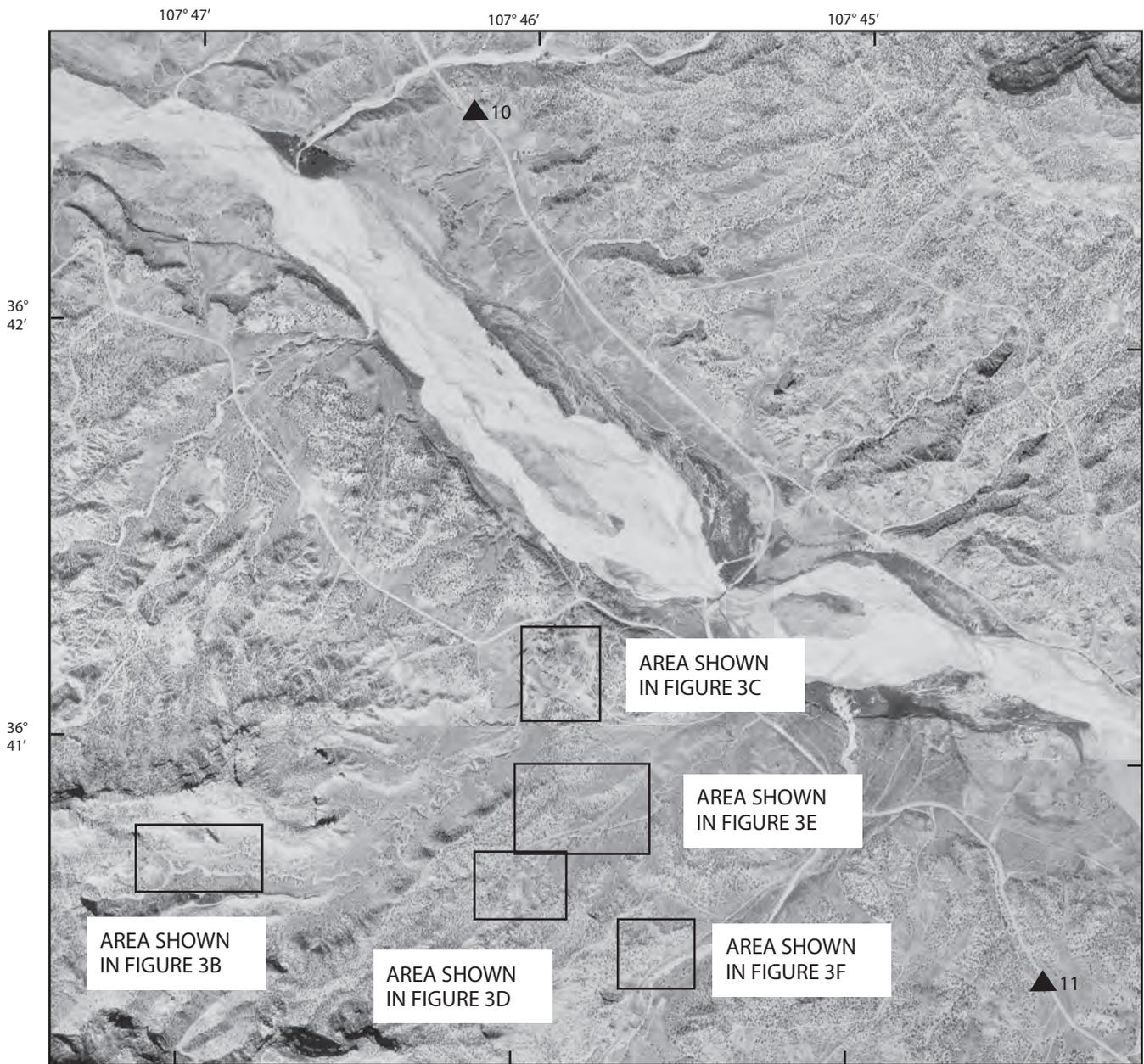
Dams

Sediment dams (dams) were installed at 43 sites. Of the 43 dams, 21 were installed on hillsides upslope from roads or well pads, 11 at the downslope edges of roads, and 11 at the downslope edges of well pads (figs. 3A-F and 4A-C). The placement of dams was designed to measure the amount of eroded sediment entering and leaving roads and well pads from both the sandstone and shale source areas. Hillslope erosion was measured by dams placed upslope from roads and well pads, and road and well-pad erosion was measured by dams placed downslope from roads and well pads. In part, dam placement was designed to test the limits of dams to measure erosion; it was anticipated that not all locations would be successful at trapping transported sediment. Fewer locations for dam placement downslope from roads were available than upslope from roads. Locations identified were pre-existing drainages with drainage areas often exceeding the trapping capacity of the dams. Adequately stabilizing the dams in the downslope locations was not possible; even when a net accumulation of sediment was recorded over a measurement interval, sediment loss from the dams was sometimes substantial. Many of these dams worked well until runoff during large monsoonal storms of the second summer (2002) produced sufficient runoff to overwhelm the dams.

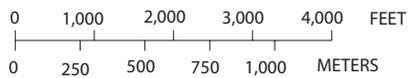
Initial attempts to measure sediment accumulation using dams made of straw bales were abandoned when the straw proved to be an irresistible draw to hungry cattle. These straw bale dams were replaced with dams made of black woven-polyethylene silt fence (commonly used during road construction to limit sediment transport from disturbed-soil areas). Dams constructed of silt fence were less sturdy than those constructed of straw bales and required regular maintenance because of persistent gusty winds. The dams were reinforced with closely spaced wood lathe and were lined with chicken wire for stability. The bottom edges of the silt fence material were buried about 0.5 ft below land surface to minimize piping and sediment loss under the dams. Hydraulic forces during large runoff events, however, still caused piping beneath some dams and the consequent erosion and loss of sediment.

Dam sizes and shapes, adapted to local topography, averaged 4 ft wide. The volume of sediment accumulation behind each dam was measured using 4-ft lengths of steel construction reinforcement bar (rebar) that generally were placed 2 ft apart in a three by three grid (depending on the size of the dam). Each section of rebar was hammered about 2 ft into the ground. The elevations of the top of each section of rebar and of each reinforcing wood lathe were surveyed to within 0.003 ft and were referenced to a stable elevation reference marker nearby. The horizontal spacing between the rebar and lathe and the initial height of each piece of rebar and lathe above ground surface were measured to within 0.05 ft. Subsequently, the height of each rebar and lathe above ground surface was measured to determine the volume of sediment that had accumulated behind the dam. The interval between successive measurements was 4-

6 Effects of Roads and Well Pads on Upland Erosion in the Largo Canyon Watershed, New Mexico, 2001-02



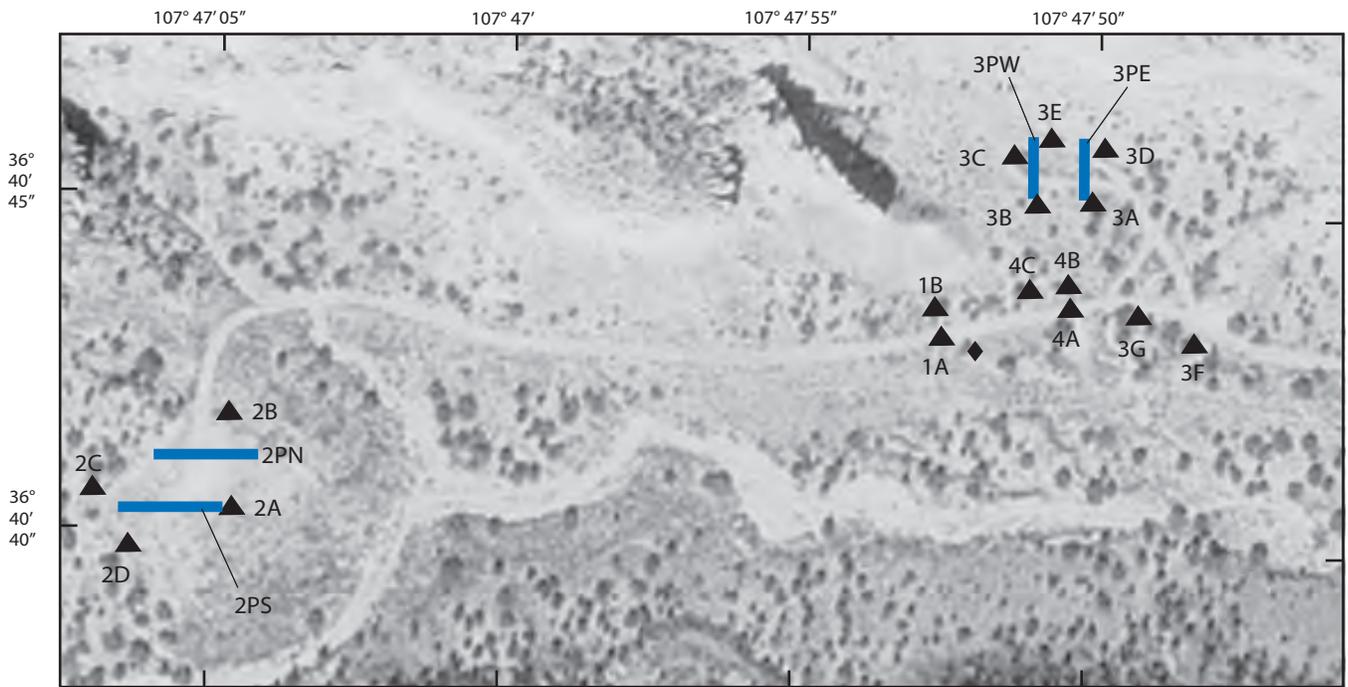
Base from U.S. Geological Survey Digital Orthophoto
Quarter Quadrangle, 1997, 1:10,000
Universal Transverse Mercator projection, zone 13



EXPLANATION

▲ 11 Sediment dam and number

Figure 3A. Location of sediment dams in the Harris Canyon area.



Base from U.S. Geological Survey Digital Orthophoto
 Quarter Quadrangle, 1997, 1:10,000
 Universal Transverse Mercator projection, zone 13

EXPLANATION

- ▲ 1A Sediment dam and number
- ◆ Precipitation gage installed for study
- 2PS Transect and number

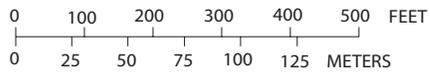


Figure 3B. Location of sediment dams 1A, 1B, 2A–2D, 3A–3G, and 4A–4C, precipitation gage installed for study, and transects 2PN, 2PS, 3PW, and 3PE, in the Harris Canyon area.

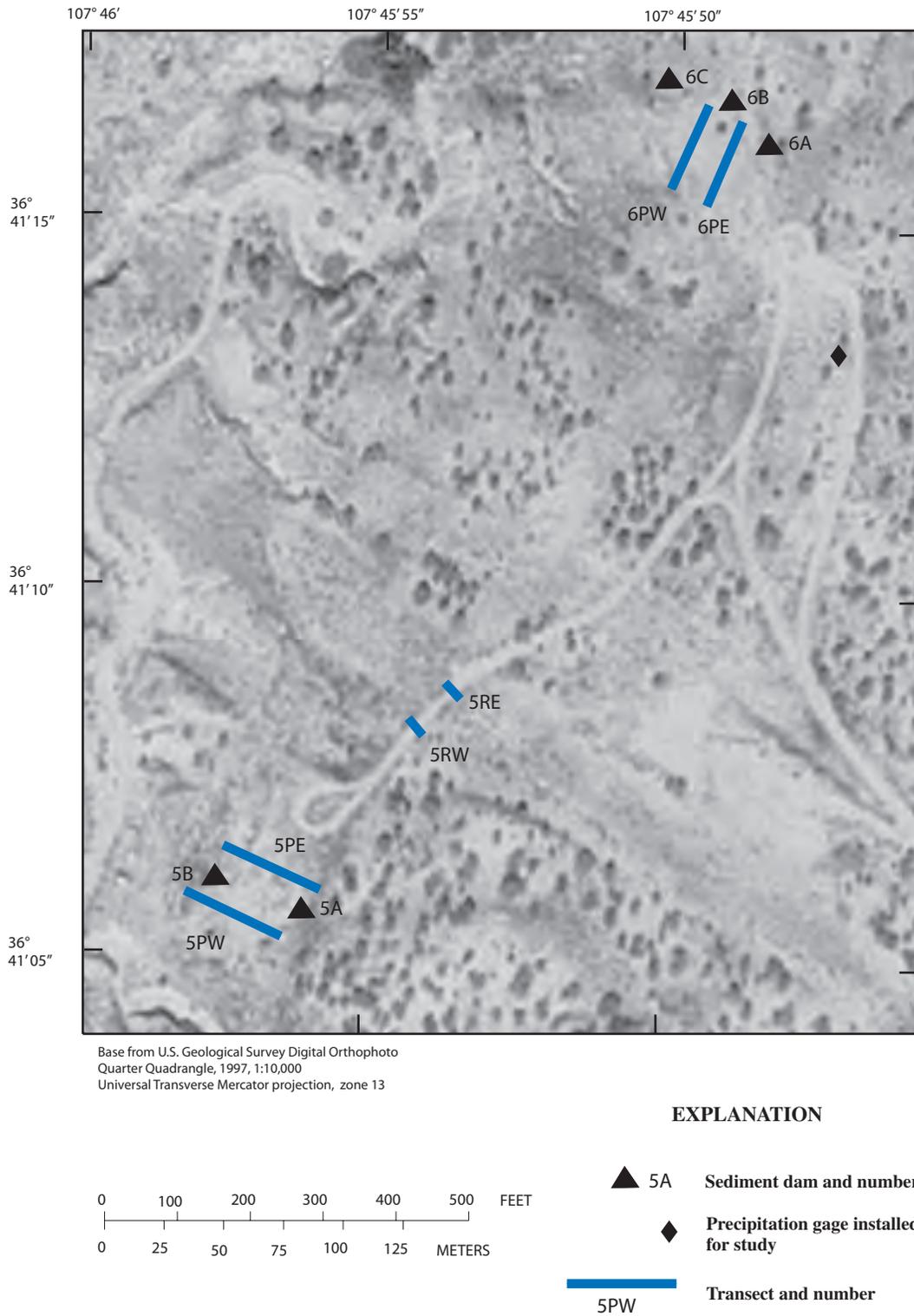
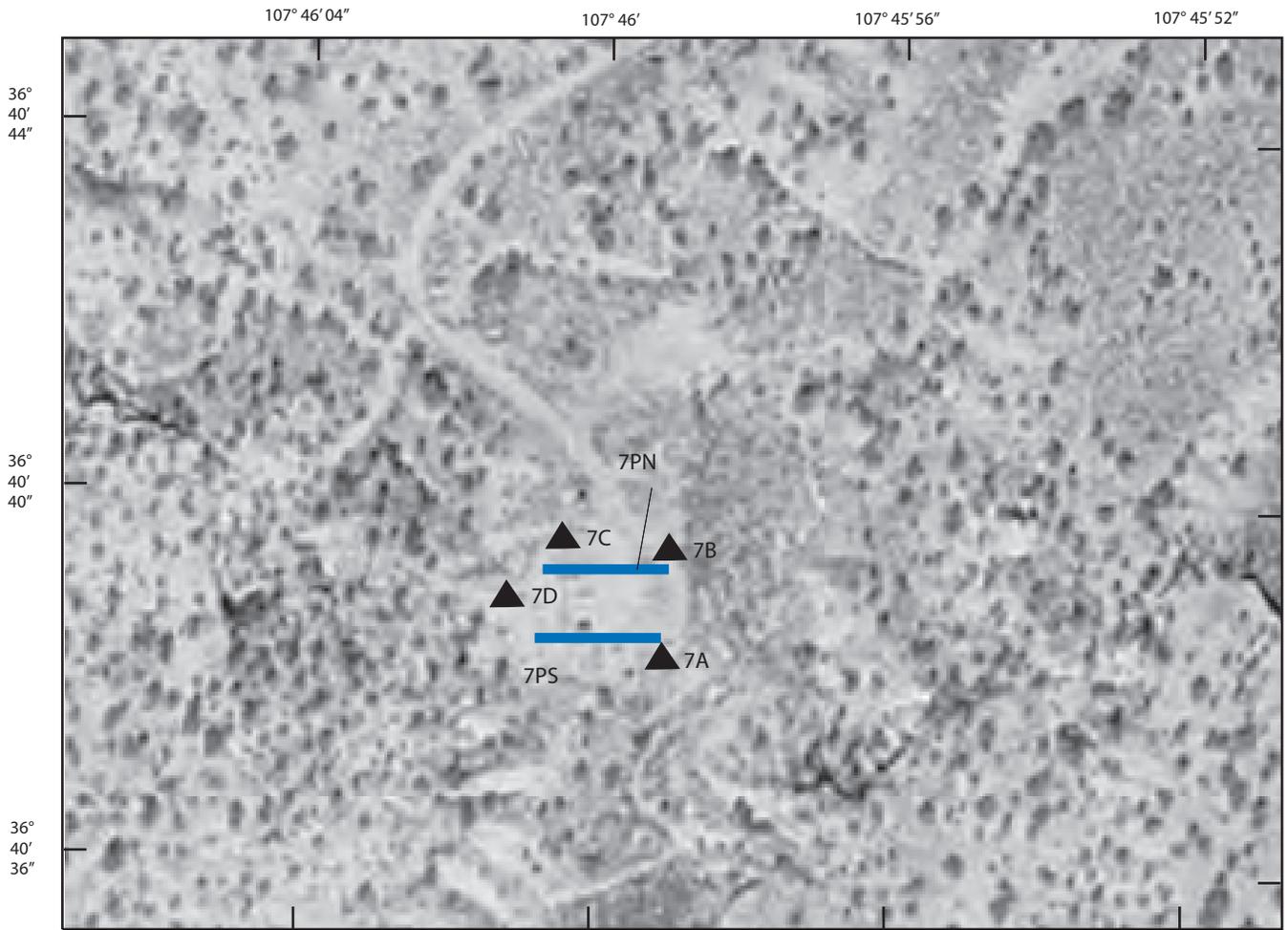


Figure 3C. Location of sediment dams 5A, 5B, and 6A–6C, precipitation gage installed for study, and transects 5PE, 5PW, 5RE, 5RW, 6PE, and 6PW, in the Harris Canyon area.



Base from U.S. Geological Survey Digital Orthophoto
Quarter Quadrangle, 1997, 1:10,000
Universal Transverse Mercator projection, zone 13

EXPLANATION

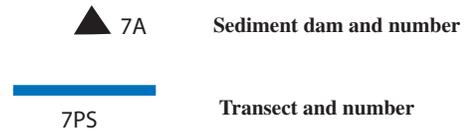
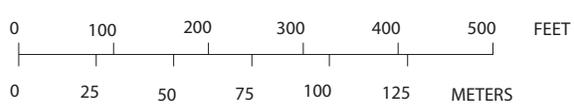


Figure 3D. Location of sediment dams 7A–7D and transects 7PN and 7PS, in the Harris Canyon area.

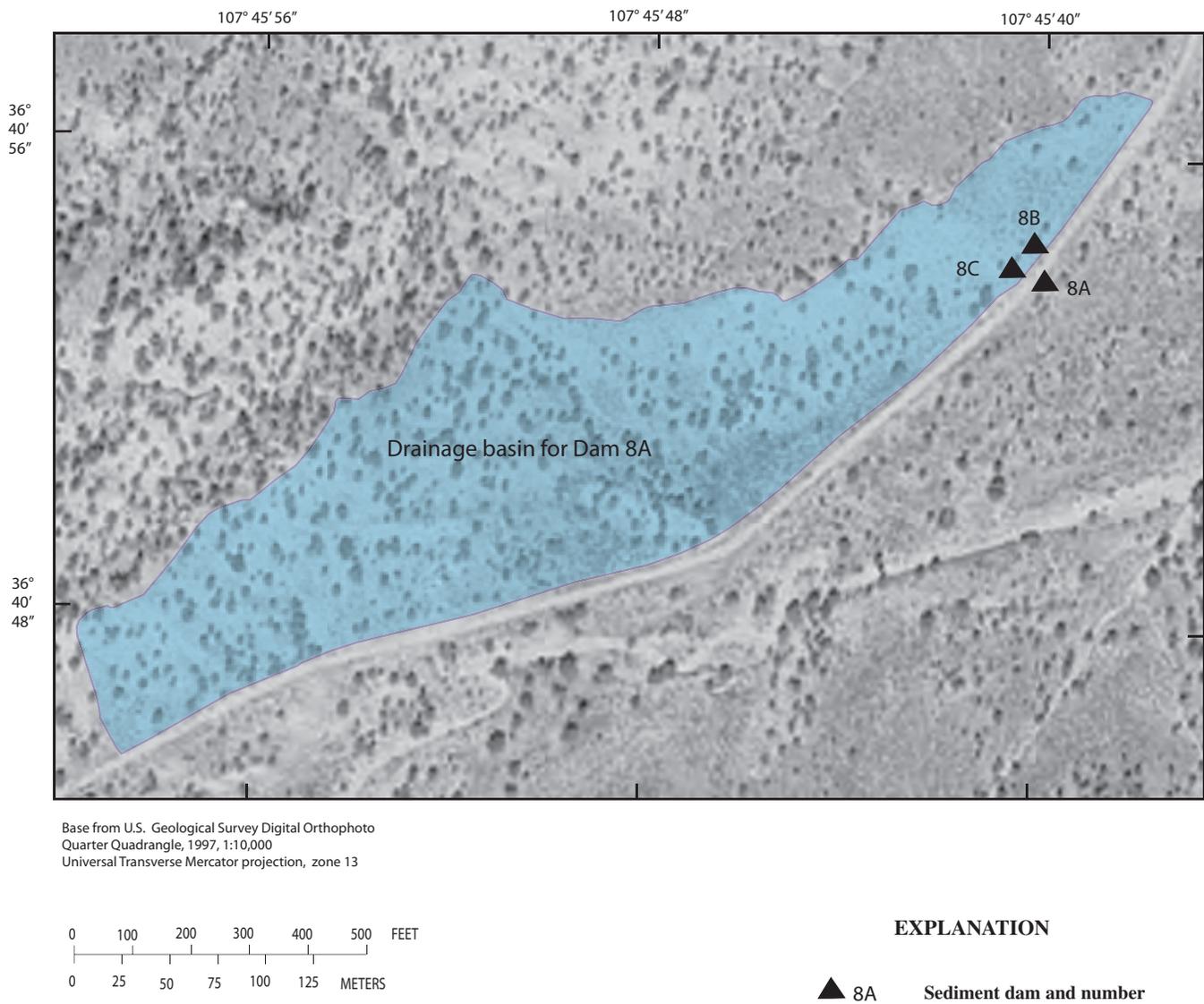
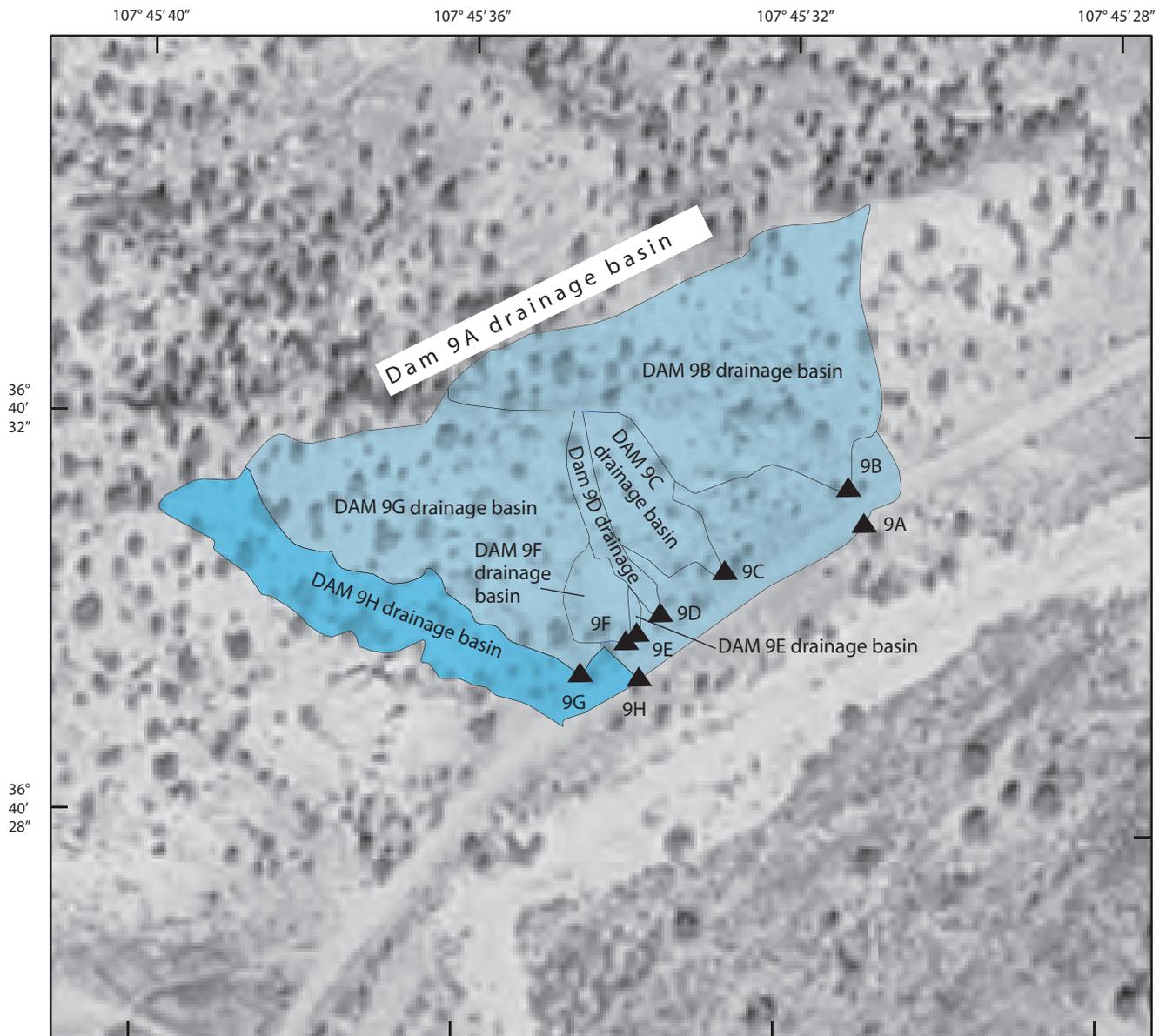
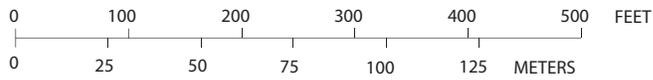


Figure 3E. Location of sediment dams 8A–8C and drainage basin for dam 8A in the Harris Canyon area.



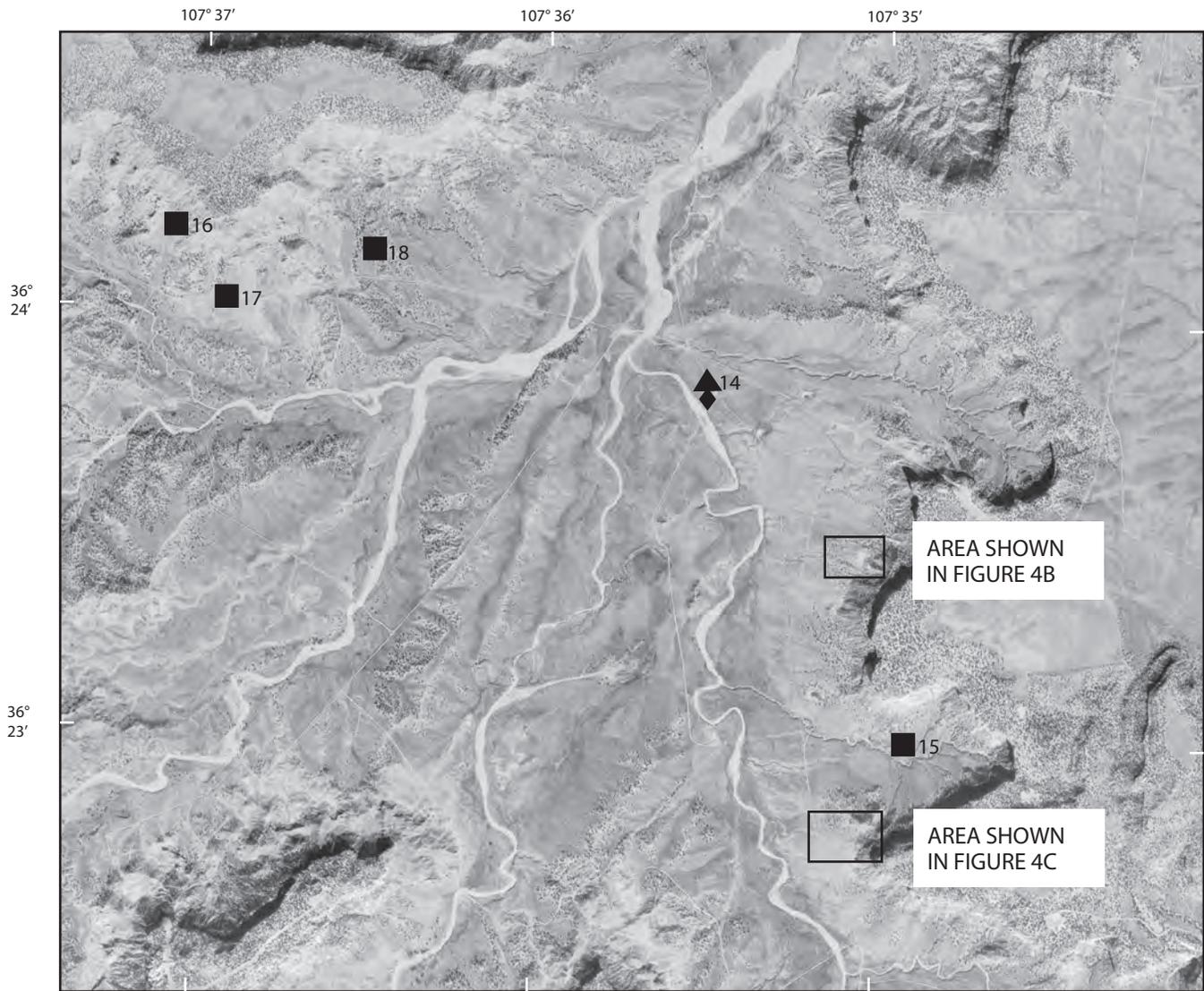
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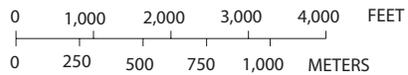
EXPLANATION

▲ 9H Sediment dam and number

Figure 3F. Location of sediment dams 9A–9H and corresponding drainage basins in the Harris Canyon area.



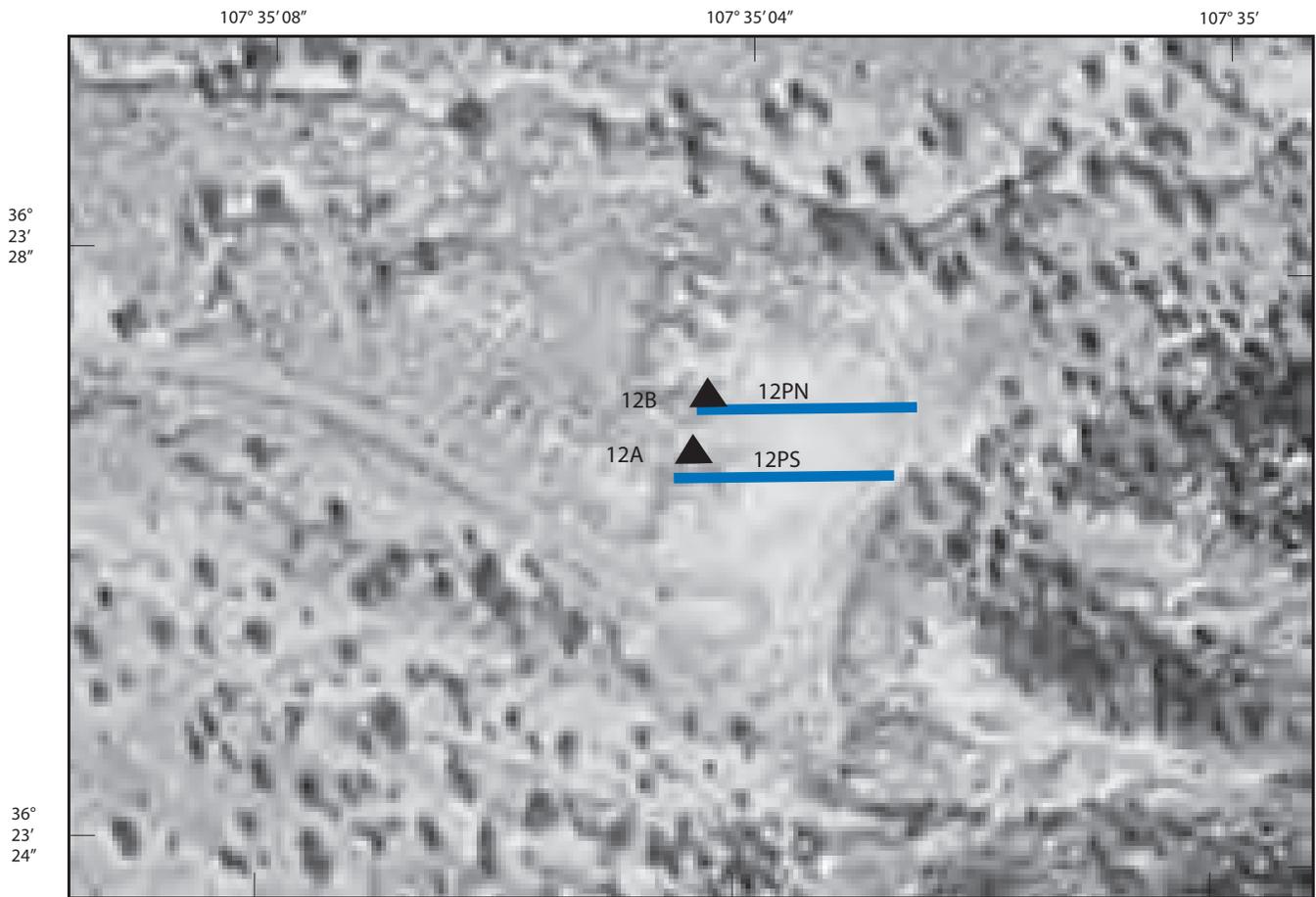
Base from U.S. Geological Survey Digital Orthophoto
 Quarter Quadrangle, 1997, 1:10,000
 Universal Transverse Mercator projection, zone 13



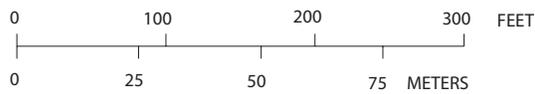
EXPLANATION

- ▲ 14 Sediment dam and number
- ◆ Precipitation gage installed for study
- 15 Location of transects and site number

Figure 4A. Location of sediment dams, precipitation gage installed for study, and transects in the Palluche Canyon area.



Base from U.S. Geological Survey Digital Orthophoto
 Quarter Quadrangle, 1997, 1:10,000
 Universal Transverse Mercator projection, zone 13



EXPLANATION

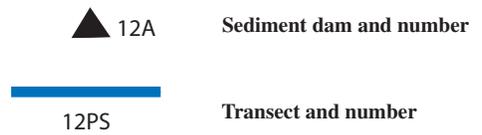


Figure 4B. Location of sediment dams 12A and 12B and transects 12 PN and 12PS in the Palluche Canyon area.

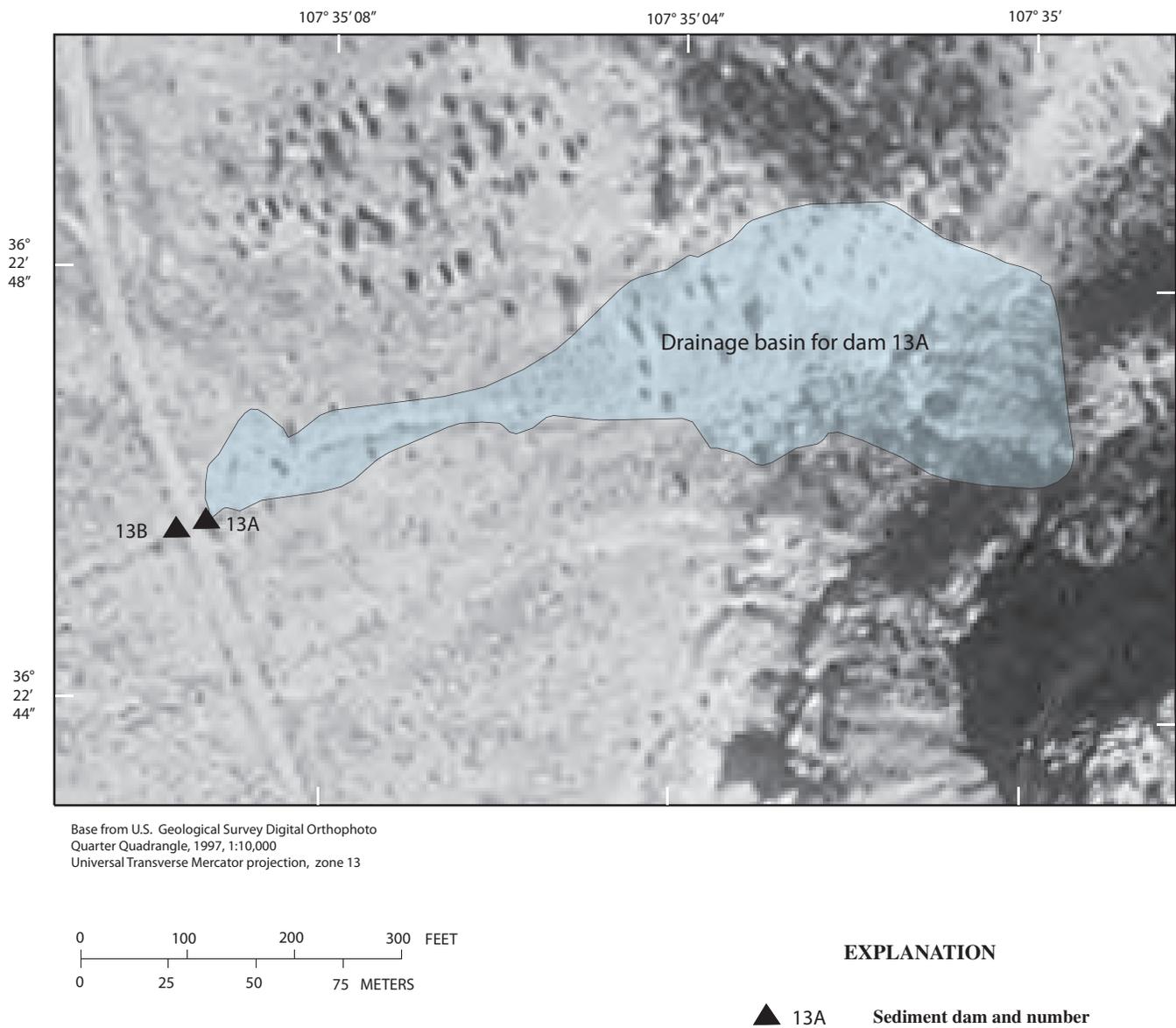


Figure 4C. Location of sediment dams 13A and 13B and drainage basin for dam 13A in the Palluche Canyon area.

6 weeks, and the accuracy of each measurement was within 0.02 ft.

Changes in sediment volume between successive measurements were calculated using the Surfer contouring program (Golden Software, Inc., 2002). Data for individual measurement intervals over which there was a net loss of sediment due to dam failure were discarded from the data set. All data for a dam were eliminated if data for more than 50 percent of the measurement intervals indicated a net loss of sediment. Using these criteria, data for 26 of 43 dams were retained for analysis (table 1).

Sediment cores were collected for grain size analysis from material inside and about 1 foot from the face of each dam. A 1-inch-diameter hand auger was used and sediment was cored to a depth of 8 to 12 inches. Sediment density (weight per unit volume) was determined for each core sample. A single end-member sample was collected from both a sandstone and a shale outcrop. The material was analyzed by the USGS Sediment Laboratory in Iowa using a combination of sieve, visual accumulation (VA) tube, and pipet analysis (Guy, 1969). The cores sampled material deeper than the sediment collected during the study. Dams were installed without altering the ground surface or drainage, and material collected was assumed to be representative of prior sediment deposition at the site.

The erosion rate for each measurement interval was expressed as volume of sediment accumulated (in cubic feet) divided by the accumulation interval (expressed as fraction of a year). The drainage area of each dam was measured at the end of the data-collection period, using either a survey tape or a Global Positioning System (GPS) receiver to establish dimensions. Drainage area boundaries determined using a GPS receiver are shown in figures 3 and 4. Slope was determined using an inclinometer. The percentage of bedrock in each drainage area was estimated by visual inspection in the field. Sediment contributing area is defined as the non-bedrock part of the drainage area.

Roads and Well Pads

Erosion of roads and well pads was measured directly using repeated surveys of monumented transects. This technique was used to monitor broad areal extents of roads and pads, supplementing the sediment-accumulation point measurements at dams. Pairs of survey transects (transects) were established across opposite sides of nine well pads (figs. 3B-D; fig. 4B). Dams were installed at six of these pads. At two road locations (figs. 3 and 4A), transects were used to monitor surface changes on road segments lacking natural drainage outlets suitable for dams. The ends of each transect were monumented with rebar, and intermediate measurement points were marked with whisker flagging generally placed at 6-ft intervals across the pad. Road transects were measured at 1-ft intervals determined by stretching a survey tape between the rebar monuments. Ground-surface elevations along transects were determined by level survey.

Transects were measured three times during the study. Each level survey was closed to within 0.003 ft (vertical). Where the horizontal measuring points were marked by whisker flagging, the accuracy of using the same horizontal measuring points as used in previous surveys was within 0.01 ft. When flagging was lost, a survey tape was used to determine the horizontal measuring points along the transect between the rebar monuments. The horizontal measurement error was +/- 0.5 ft. Changes in cross-sectional areas between surveys are reported to 1.0 ft².

Incipient erosion from road berms was characterized by counting the number of erosion cuts per specified length of the berm on both sides of the road surface. Erosion cuts were defined as vertical erosion cuts down the berm face at least 0.5 in. deep. The specified length of a berm was dependent on the road configuration and the length of road for which geomorphic conditions remained similar.

Roads and well pads in the Harris Canyon and Palluche Canyon road- and pad-analysis areas (fig. 2) were digitized from USGS Digital Orthophoto Quarter Quadrangles (DOQQ's), 1:10,000-scale to the North American Datum of 1983 (NAD83) on a Universal Transverse Mercator (UTM) projection. The aerial photographs upon which the DOQQ's are based were taken in October 1997. The ground resolution of the DOQQ's is 1 m (3.3 ft).

Precipitation

Graduated plastic rain gages were installed near dams 1A and 6C (figs. 3B and 3C) in the Harris Canyon area and near dam 14 (fig. 4A) in the Palluche Canyon area and were read when the dams were measured. Cork in the gages gave a reading of maximum total recorded during the measurement period but did not control for evaporation. Tipping-bucket rain gages were installed at the same locations during the second year and recorded precipitation data from June 26 to November 26, 2002.

Statistical Analysis

Average erosion rate from each of the three landscape positions was tested against each of the potential influencing parameters using regression analysis. Regression analysis relates a dependent variable to one or more independent causative variables, evaluated by the standard error and the coefficient of determination, R^2 (Minitab, 2003). R^2 is the proportion of the variation in the dependent variable Y explained by the regression equation. The adjusted R^2 adjusts the calculation of the coefficient of determination for a population with a small number of observations. A p -value, calculated for each independent variable, represents the probability that the relation of that variable in the regression is due to chance, with values less than or equal to 0.05 defining a statistically significant variable.

Mann-Whitney is a non-parametric two-sample t -test used to compare the means of two populations of samples with unequal variances (Minitab, 2003). This statistic was used to

Table 1. Sediment yield, drainage area, erosion rate, slope, land use, and landscape position of sediment dams and percentage of sand, silt, and clay of sediment trapped behind sediment dams.

[Due to sediment losses, data for 26 dams were retained for analysis]

Sediment dams (figs. 3 and 4)	Average sediment yield from drainage basin, in cubic feet per year	Drainage area, in square feet	Drainage area, in acres	Percentage of drainage area that is bedrock	Contributing area (drainage area minus bedrock area), in square feet	Normalized average erosion rate, in feet per year	Slope of contributing area, in percent	Land use	Landscape position	Percentage of sand, silt, clay		
1A	79.9	128,000	2.9	61	49,700	0.00165	6	Grazed	Below road	74.2	15.3	10.5
1B	39.1	9,300	0.2	0	9,300	0.00411	39	Grazed	Hillslope	70.9	14.8	14.3
2A	9.3	500	0.0	0	500	0.01877	14	Grazed	Below well pad	83	9	8
2B	9.9	2,300	0.1	0	2,300	0.00429	10	Grazed	Below well pad	76	12	12
2D	45.8	332,000	7.6	85	46,600	0.00098	35	Grazed	Hillslope	91	5	4
3A	24.5	1,800	0.0	0	1,800	0.01336	5	Grazed	Below well pad	85	8	7
3B	6.5	590	0.0	0	590	0.01098	17	Grazed	Below well pad	85	7	8
3D	3.5	2,500	0.1	0	2,500	0.00142	43	Grazed	Hillslope	76	11	12
4A	9.5	76,800	1.8	48	40,000	0.00024	11	Grazed	Below road	59	23	17
4B	3.3	35,300	0.8	18	28,900	0.00011	34	Grazed	Hillslope	49	30	21
4C	2.7	29,600	0.7	43	16,800	0.00016	28	Grazed	Hillslope	50	28	22
5A	13.2	1,000	0.0	0	1,000	0.01338	8	Grazed	Below well pad	82	9	9
6C	11.2	680	0.0	0	680	0.01653	26	Grazed	Hillslope	87	8	5
7B	3.6	580	0.0	0	590	0.00613	11	Grazed	Below well pad	83	9	8
7C	3.4	4,900	0.1	0	4,900	0.00070	26	Grazed	Hillslope	33	36	31
7D	10.6	4,500	0.1	0	4,500	0.00237	30	Grazed	Hillslope	85	10	5
8B	12.1	3,500	0.1	0	3,500	0.00344	22	Grazed	Hillslope	88	7	5
8C	8.9	3,400	0.1	0	3,400	0.00259	22	Grazed	Hillslope	88	7	5
9D	8.2	4,900	0.1	0	5,000	0.00165	20	Grazed	Hillslope	56	25	19
9E	2.4	470	0.0	0	470	0.00502	20	Grazed	Hillslope	77	9	14
9F	4.7	5,000	0.1	15	4,200	0.00111	20	Grazed	Hillslope	80	9	11
9H	11.2	32,000	0.7	30	22,400	0.00050	6	Grazed	Below road	86	6	8
12A	2.8	340	0.0	0	340	0.00828	4	Ungrazed	Below well pad	4	55	41
12B	4.7	300	0.0	0	300	0.01548	4	Ungrazed	Below well pad	11	45	44
13B	8.2	5,800	0.1	0	5,800	0.00142	2	Ungrazed	Below road	73	14	13
14	4.8	4,100	0.1	0	4,100	0.00117	1	Ungrazed	Below road	58	18	24

test for a statistical difference between the average erosion rate of the three landscape positions with each of the other two positions. A p-value less than or equal to 0.05 was considered to represent a significant difference in erosion rates.

Effects of Roads and Well Pads on Upland Erosion

In the following sections, data collected during this study are used to establish minimum erosion rates for hillslopes, the downslope edges of roads, and well pads. Field observations made during this study are used to develop a conceptual model of processes of upland erosion in the study area that incorporates the effects of roads and well pads on the erosion process.

Based on the October 1997 DOQQ's, the Harris Canyon road- and pad-analysis area (fig. 2) contains 108 well pads with a combined area of 0.1 mi², or 64.5 acres, and 84 mi of roads with a road density of 2.5 mi/mi². The Palluche Canyon road- and pad-analysis area (fig. 2) contains 114 well pads with a combined area of 0.04 mi², or 28.8 acres, and 114 mi of roads with a road density of 2.2 mi/mi². With the exception of county-maintained roads, the roads are not crowned or ditched and were graded only occasionally when heavy use on wet roads resulted in a rutted surface.

Precipitation

Precipitation at four National Weather Service climatological stations (fig. 1) for the 2001-02 study period generally followed the seasonal monsoonal pattern but with an unusually dry spring in 2002 and little rain recorded for the first 6 months of that year (fig. 5). Mean annual precipitation at the four stations was below normal for 2001-02 (table 2). During 2001 precipitation was generally of low intensity. During the 2002 monsoon season, however, precipitation of high intensity fell several times. The first high-intensity precipitation that fell in the Palluche Canyon area on July 9, 2002, totaled 0.82 in., with a maximum intensity of 0.71 in./hr. The second high-intensity precipitation that fell on July 23, 2002, in the Harris Canyon area totaled 1.4 in. over about 4 hours, with a maximum intensity of 0.68 in./hr. Although precipitation data were not recovered for tipping-bucket rain gages in the Harris Canyon area in August 2002 due to an equipment malfunction, data from the four National Weather Service climatological stations and from the Palluche Canyon area tipping-bucket rain gage indicate sparse precipitation. Three major rains fell during September 2002, the largest a storm totaling 0.47 in. over 32 minutes near the end of the month.

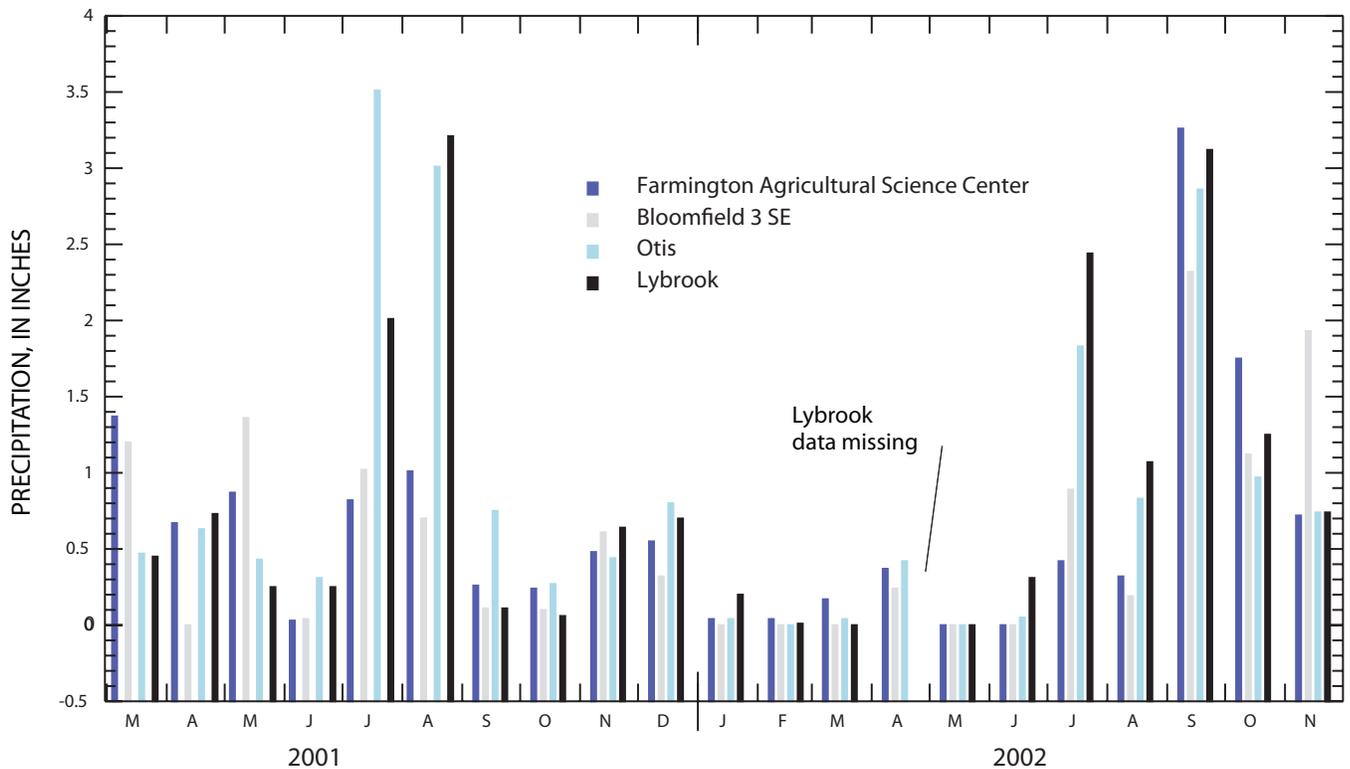


Figure 5. Total monthly precipitation at the Farmington Agricultural Science Center, Bloomfield 3 SE, Otis, and Lybrook National Weather Service cooperative climatological stations, March 2001–November 2002. Data obtained from Western Region Climate Center, 2004.

Table 2. Mean annual precipitation for the Farmington Agricultural Science Center, Bloomfield 3 SE, Otis, and Lybrook climatologic stations (2001-02) and the National Weather Service 30-year (1971-2000) normal precipitation.

[Data obtained from Western Region Climate Center, 2004]

Time period	Precipitation, in inches				Mean annual precipitation for the four climatologic stations
	Farmington Agricultural Science Center	Bloomfield 3 SE	Otis	Lybrook	
2001	7.54	7.09	12.34	10.49	9.37
2002	7.69	7.30	8.39	9.89	8.32
30-year normal	8.39	9.18	10.23	10.20	9.50

Erosion Rate

Sediment accumulation behind dams, recorded for 17 intervals of time (measurement intervals), was used to determine the average erosion rate for each dam in cubic feet per year. To compare erosion rates among dams collecting sediment from drainage areas of varying sizes, the erosion rate was normalized by dividing by the contributing area (table 1) so that erosion rate is expressed as volume of sediment per unit area per year (cubic feet per square foot per year or feet per year). Other factors considered to influence erosion rates are intensity and amount of precipitation, percentage of bedrock in the total drainage area, slope of the contributing area, land use (grazed or ungrazed), grain size of the accumulated sediment (indicative of source material), and landscape position of the dam and drainage area on the landscape (hillslope, below a road, or below a well pad).

No attempt was made to relate precipitation intensity and amount to erosion rate for a measurement interval because the 4-6 weeks between measurements did not allow correlation of individual precipitation events to individual erosion events. Similarly, the measurement interval did not allow for the establishment of thresholds for erosion based on the intensity and duration of precipitation. In addition, given the highly variable annual and interannual precipitation patterns in an arid environment, measuring a representative sample of events in a 2-year period to establish thresholds of sediment movement is not possible.

Average erosion rates at the dams significantly related to size of the contributing drainage area ($p = 0.004$) and account for 28 percent of the regression variability in the data. The percentage of bedrock in the drainage area of a dam also signifi-

cantly related to average erosion rate (R^2 (adjusted) = 30 percent, $p = 0.003$). The parameters percent bedrock and contributing area significantly relate to each other (R^2 (adjusted) = 78 percent, $p = 0.000$), so a multiple linear regression of these two parameters to estimate erosion rate does not improve the regression. Because of the complex physical environment and difficult sampling conditions, the final data set consisting of measurements from 26 dams (table 1) was insufficient to draw relationships between erosion rates and selected geomorphic parameters. However, the average erosion rate differs significantly for dams in certain landscape positions. The average erosion rate normalized by drainage area was about 0.001 ft/yr below roads, 0.003 ft/yr on hillslopes, and 0.011 ft/yr below well pads (fig. 6; table 3). With use of a two-sample t-test to compare the means of two populations of samples with unequal variances, there was no significant difference in the average erosion rate for dams located on hillslopes and below roads, whereas average erosion rates for dams below well pads were significantly larger than for dams in the other two landscape positions.

The average erosion rates estimated from the data collected during this study most likely represent minimum erosion rates. Sediment-accumulation data for measurement intervals during which dams were breached during 2002, as a result of the large volume of runoff generated by high-intensity storms, were not used to compute erosion rates. For this reason, the higher range of erosion rates is underrepresented and the results of this study are biased toward the lower end of the range of erosion rates.

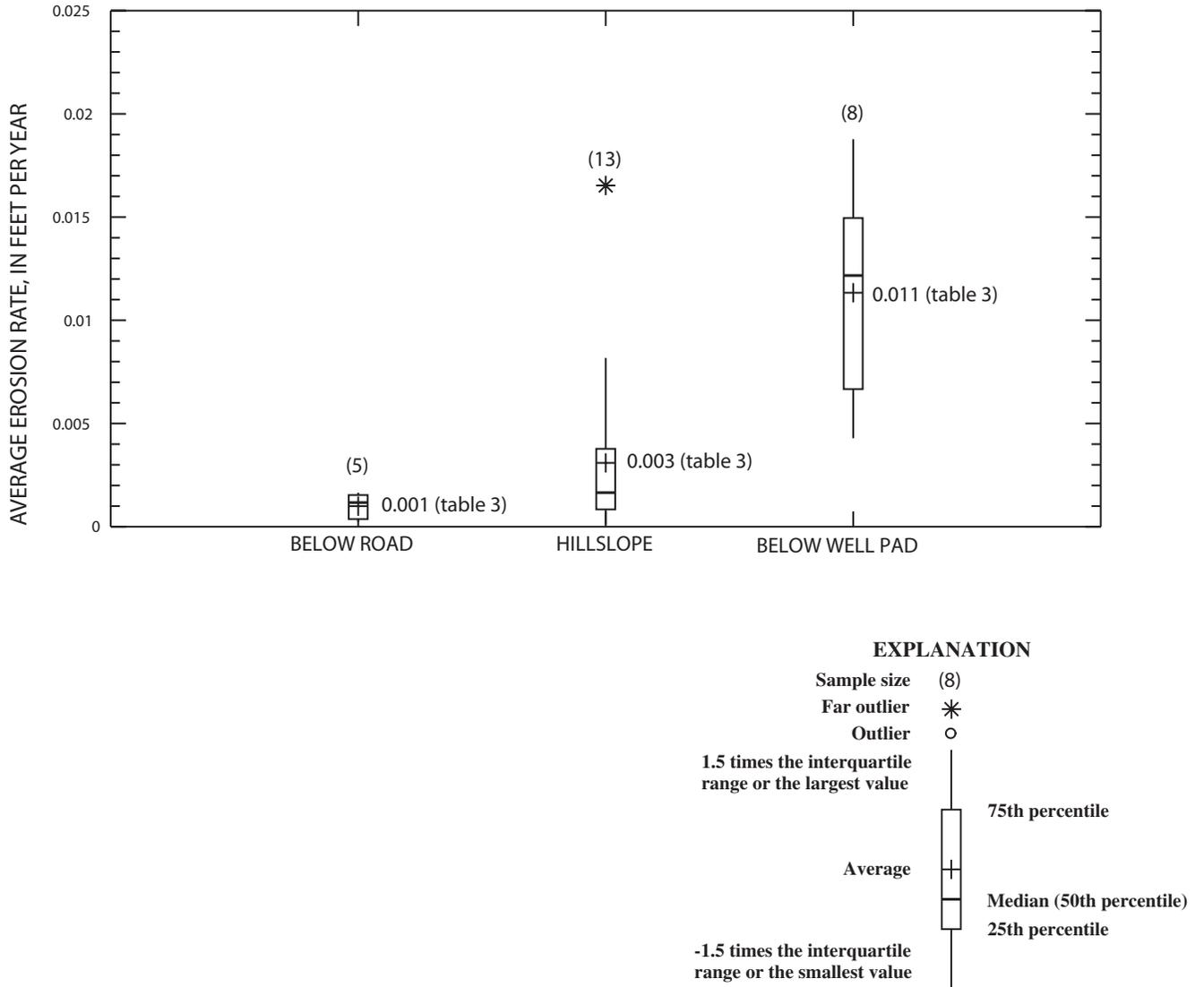


Figure 6. Average erosion rates for drainage areas located below roads, on hillslopes, or below well pads.

Table 3. Summary statistics for sediment-dam erosion rate data. P-values refers to statistical comparison of average erosion rate between two landscape positions. Below road is repeated to show p-value statistical comparison to below well pad.

Landscape position	Average, in feet per year	Standard deviation	p-value
Below road	0.001	0.001	0.111
Hillslope	0.003	0.004	0.002
Below well pad	0.011	0.005	0.001
Below road	0.001	0.001	

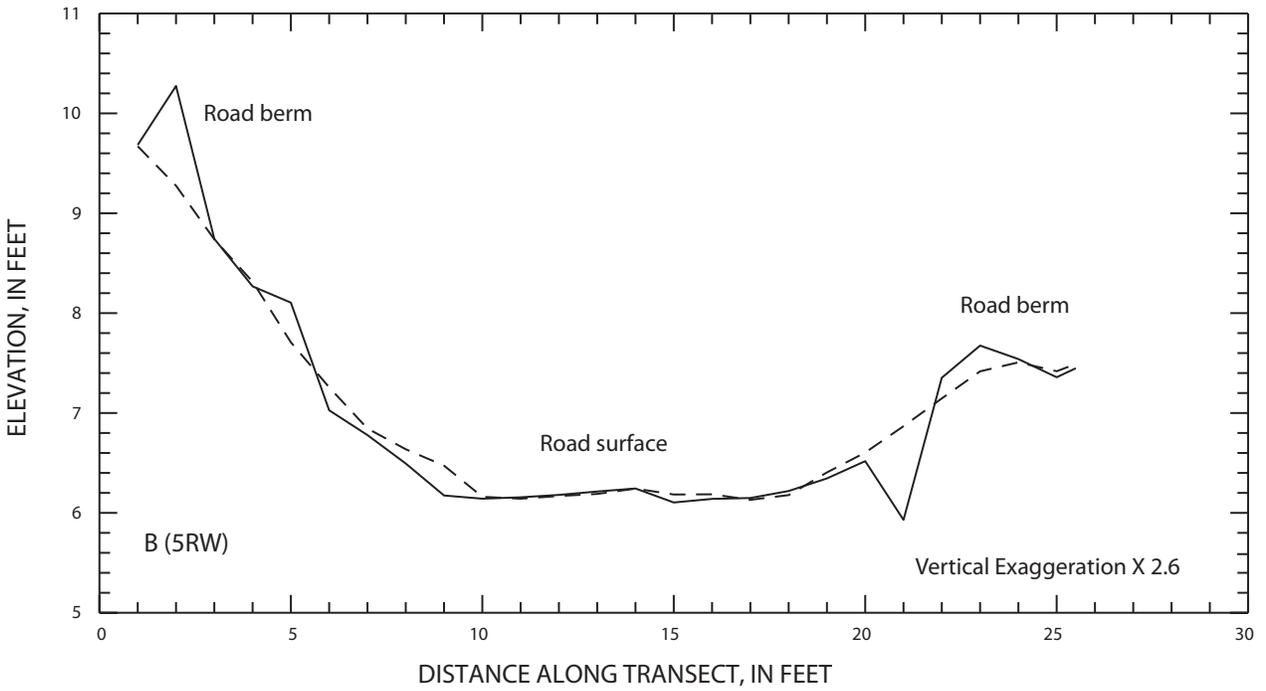
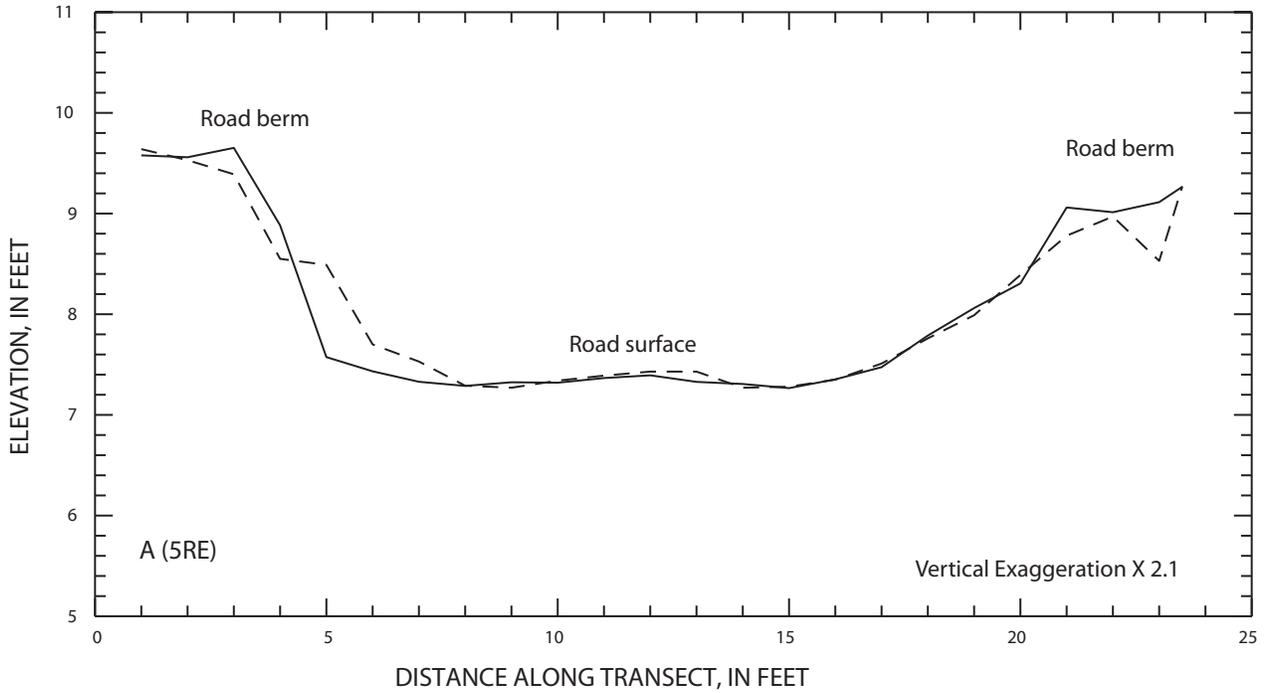
Road and Well-Pad Transects

Land-surface transects were located at two road sites and nine well pads. Although road and well-pad transects were, for the most part, surveyed three times during the study, most of the following discussion focuses on the overall change in land surface between the first (June 28, 2001) and last (November 20, 2002) surveys. All sites are discussed, but only selected sites are illustrated.

Road transects 5RE and 5RW (fig. 7), in the Harris Canyon area, were located on a sandy stretch of road with a 3-percent slope that connects well pad 5 with the feeder-road network (fig. 3C). The tops of the road berms are about 2 ft above the road surface (fig. 7), and the land slopes away from the road berms on both sides. In general, both transects show apparent downslope sediment movement from the road berms, erosion from the upper part of the berms, and redeposition on the road at the base of the berms. There is infilling of a road rut in transect 5RW, but no substantial net change in road surface elevation on either transect. Road transects 17RL, 17RM, and 17RS (fig. 8), located in the Palluche Canyon area (within area 17 in fig. 4A), cross a flat section of road through an open area adjacent to an area of badlands topography. Sandstone is adjacent to the upslope end of transect 17RS, whereas shale crops out about 200 ft from the road at the uphill end of transect 17RL. The transects are about 300 ft apart. Transect 17RL is the far-

thest upslope transect and 17RS is the farthest downslope transect. Site 17 was chosen because silt, identified by color, was observed during field reconnaissance to have been transported from the weathered outcrops across a hillslope with a 2-percent gradient and deposited across and on the far side of the road. The three transects together support sediment movement downslope toward the road; a larger volume of movement was noted in steeper portions. The transects also indicate erosion and transport of sediment downslope and along the road once the sediment reaches the road.

Well-pad transects 2PN, 2PS, 5PE, 5PW, 6PE, and 6PW (figs. 9, 10, and 11), in the Harris Canyon area, were located on sandy material. The site 2 well pad (fig. 3B), the head of a side canyon, lies downslope from colluvial sediment deposits and bedrock cliffs that potentially can supply large volumes of sediment. A loss of sediment from June 28, 2001, to November 2002 generally was shown for transects 2PN and 2PS from the hillslope above the pad and from the pad, although some sediment was deposited in transect 2PN on the pad (fig. 9). Erosion from the downslope edge of the pad is shown in transect 2PN, whereas deposition is shown in transect 2PS. The pattern of net gain and loss of sediment between successive surveys suggests downslope transport and redeposition of sediment from the hillslope, over the surface of the well pad, and down the well-pad edges.



EXPLANATION

- Elevation along transect, June 28, 2001
- - - Elevation along transect, November 20, 2002

Figure 7. Land-surface changes for transects (A) 5RE and (B) 5RW in the Harris Canyon area, June 28, 2001–November 20, 2002. Transect locations shown in figure 3C. View is to the northeast.

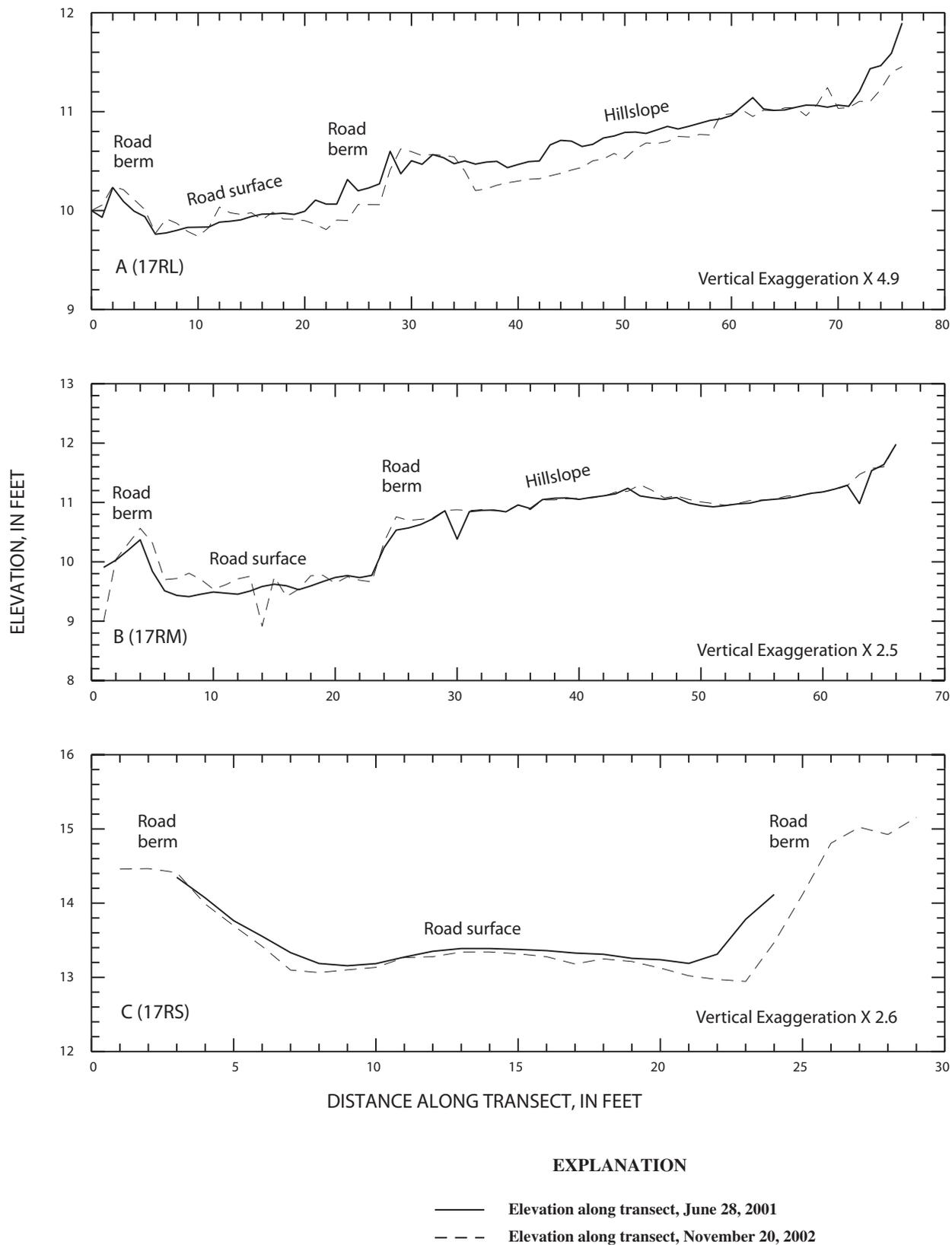
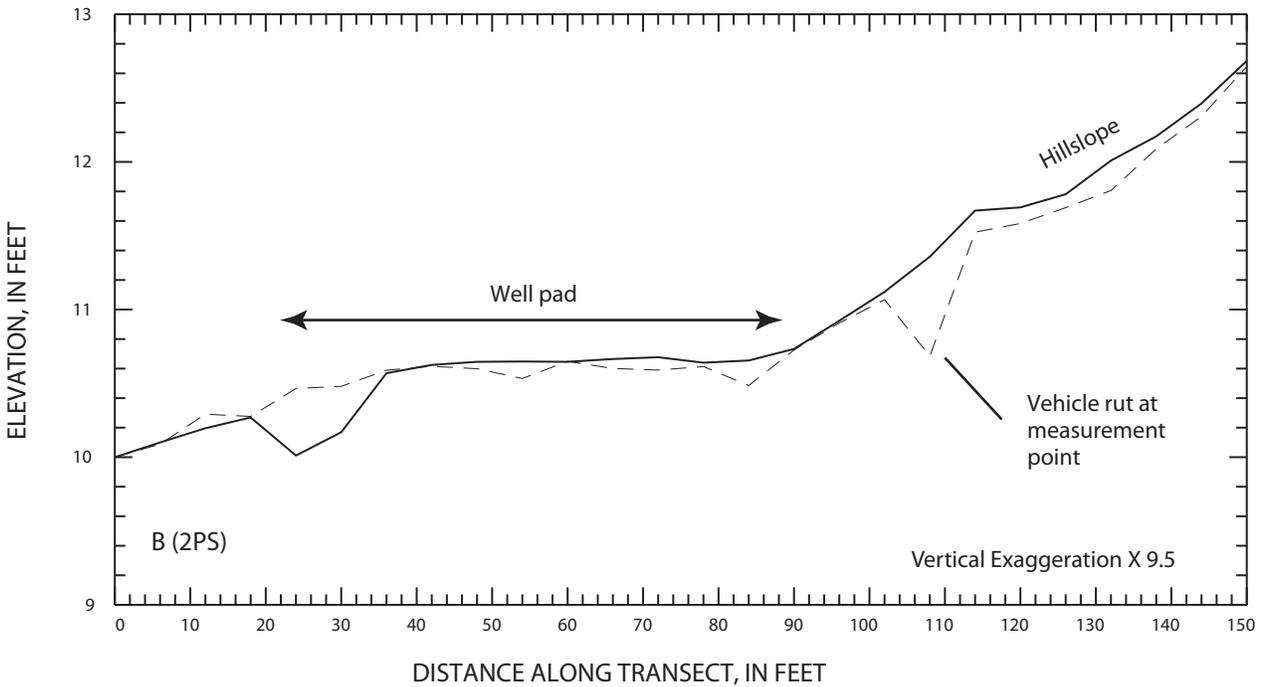
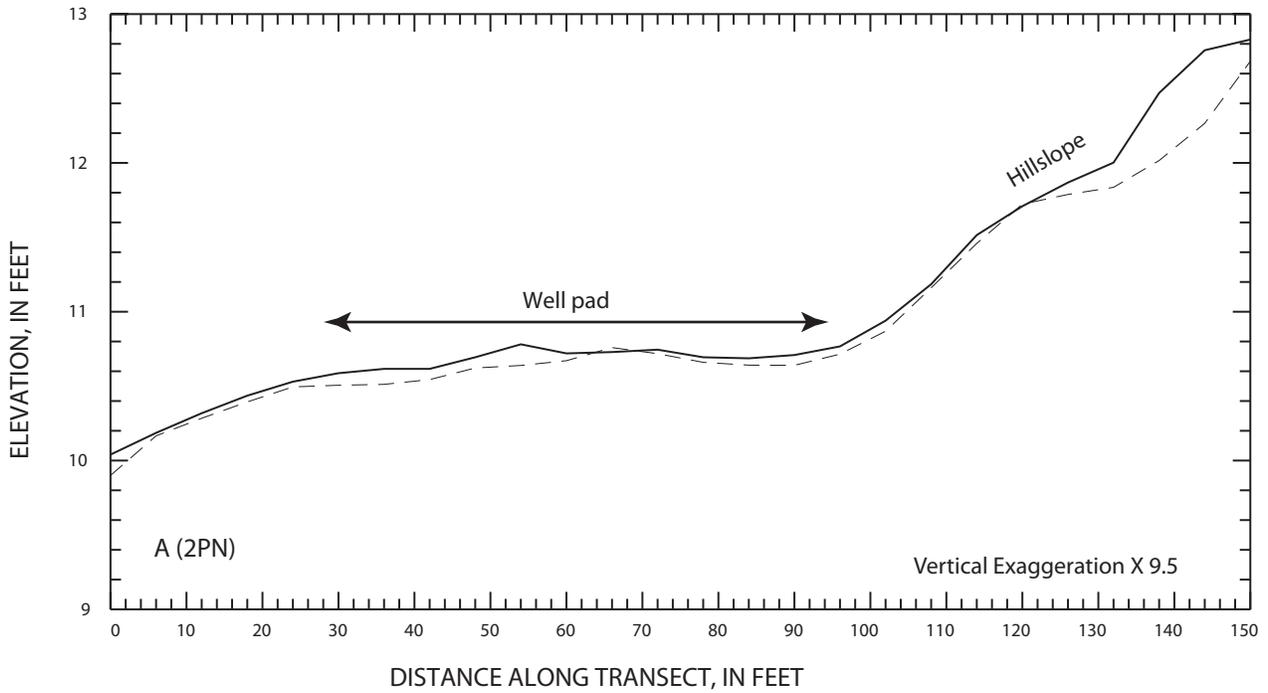


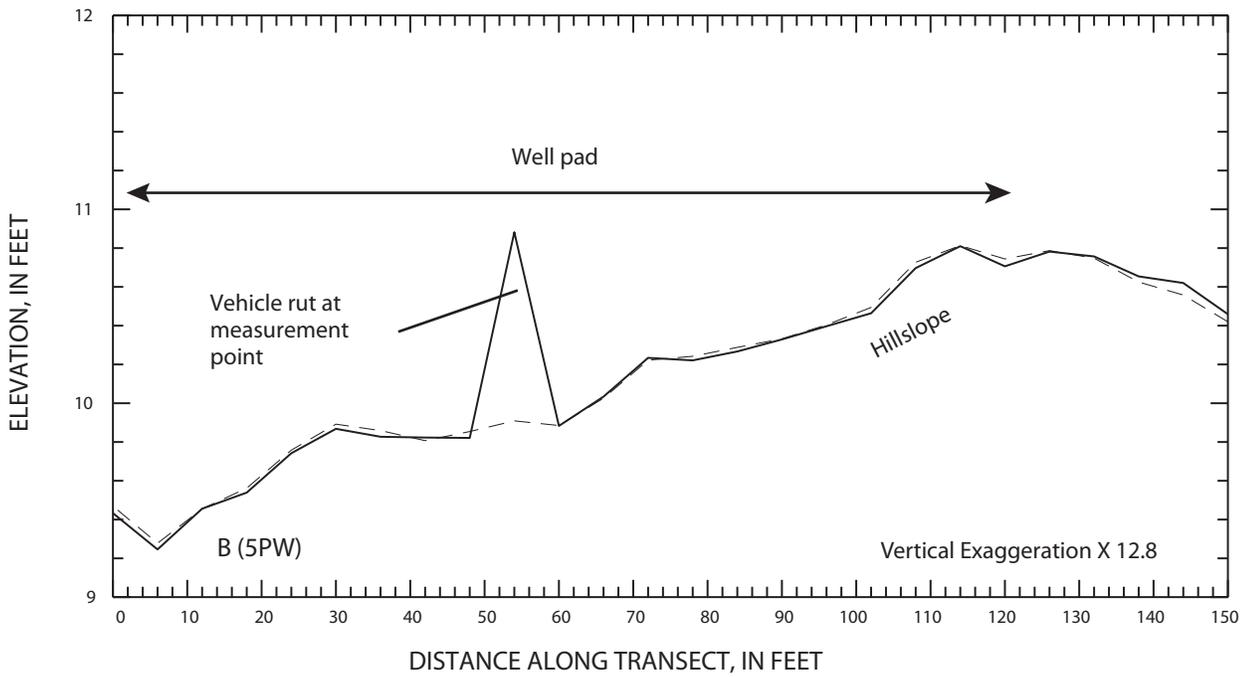
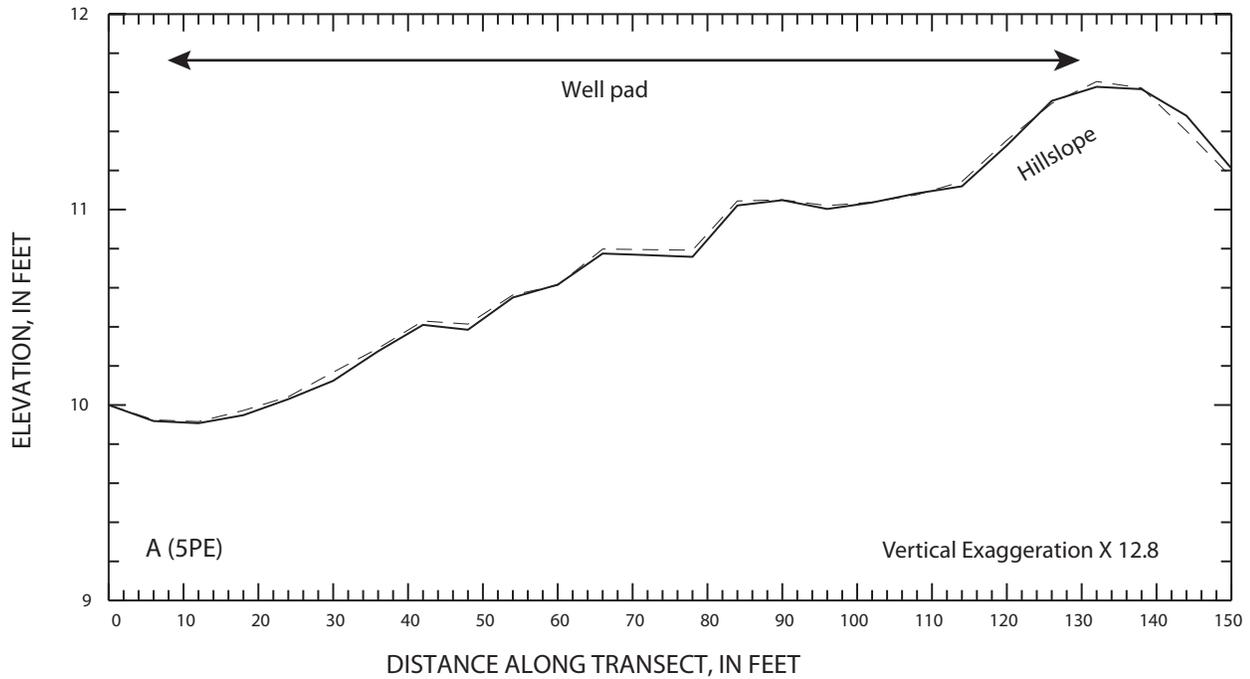
Figure 8. Land-surface changes for transects (A) 17RL, (B) 17RM, and (C) 17RS in the Palluche Canyon area, June 28, 2001–November 20, 2002. Transect locations shown in figure 4A. View is to the west.



EXPLANATION

- Elevation along transect, June 28, 2001
- - - Elevation along transect, November 20, 2002

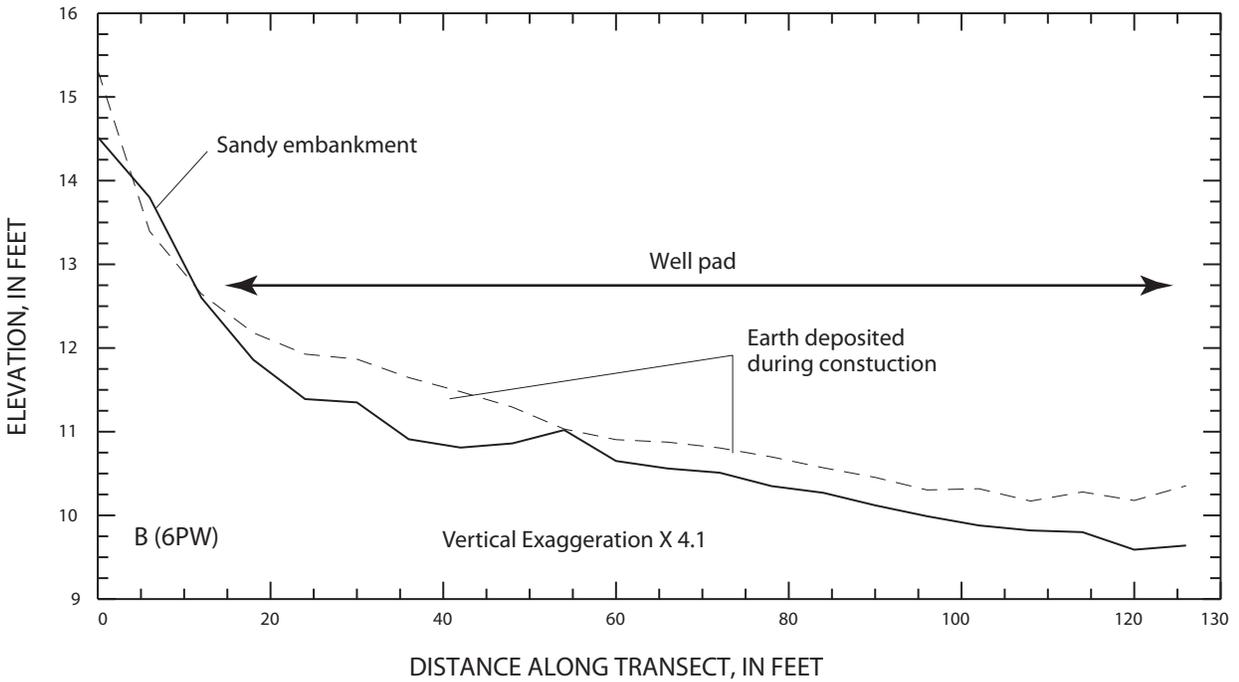
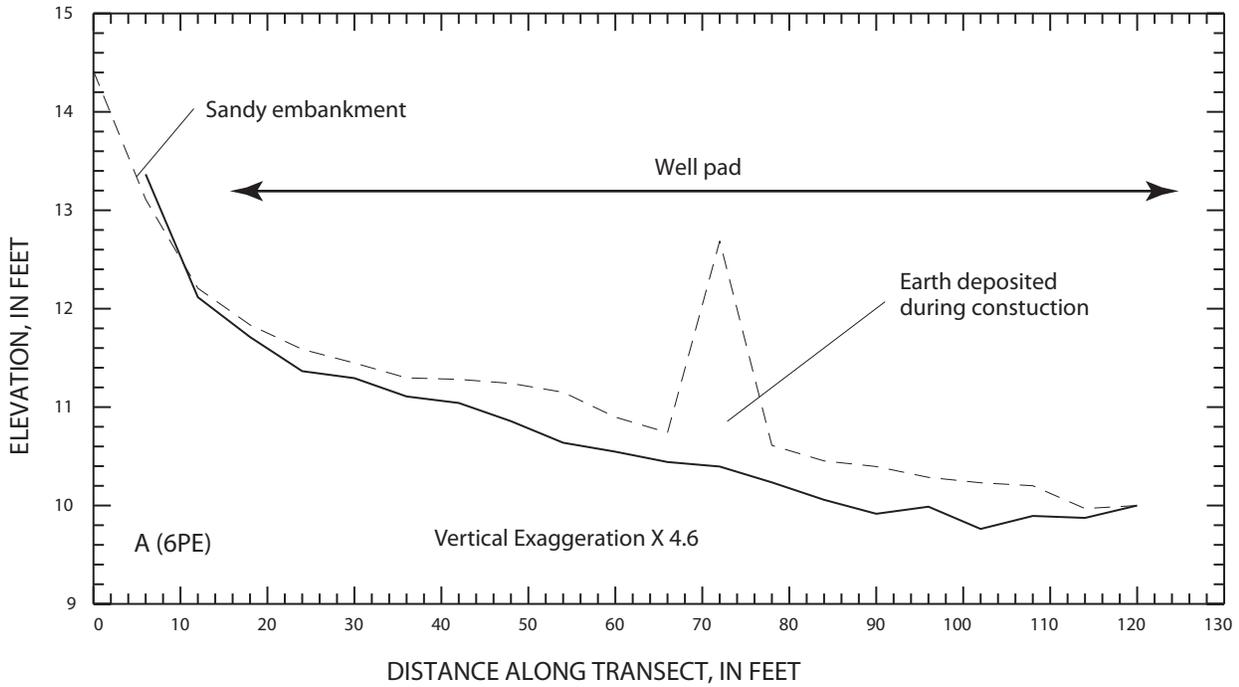
Figure 9. Land-surface changes for transects (A) 2PN and (B) 2PS, in the Harris Canyon area, June 28, 2001–November 20, 2002. Transect locations shown in figure 3B. View is to the south.



EXPLANATION

- Elevation along transect, June 28, 2001
- - - Elevation along transect, November 20, 2002

Figure 10. Land-surface changes for transects (A) 5PE and (B) 5PW in the Harris Canyon area, June 28, 2001–November 20, 2002. Transect locations shown in figure 3C. View is to the northeast.



EXPLANATION

- Elevation along transect, June 28, 2001
- - - Elevation along transect, November 20, 2002

Figure 11. Land-surface changes for transects (A) 6PE and (B) 6PW in the Harris Canyon area, June 28, 2001–November 20, 2002. Transect locations shown in figure 3C. View is to the northwest.

An intervening low area separates the site 5 well pad from the nearby hillslope, and the site 6 well pad is adjacent to a sandy embankment (fig. 3C). In transects 5PE and 5PW, a fairly stable surface configuration and some downslope sediment movement and redeposition at the edges of the well pads are shown, with the exception of vehicle ruts in the surface at transect 5PW (fig. 10). The site 6 well pad showed a similarly stable surface configuration between the first and second transect surveys (June 28, 2001, and May 7, 2002; not shown). Increases in surface elevation caused by earth movement during construction are shown in transects 6PE and 6PW (fig. 11), which compares the first and the third survey.

Sites 16 and 18 in the Palluche Canyon area (fig. 4A) also were located on sandy material. Comparison of the June 28, 2001, and November 20, 2002, survey measurements indicates a net gain of sediment on the site 16 well pad in transects 16PE and 16PW (fig. 12). The well pad at site 18 (fig. 13) was regraded before the November 20, 2002, survey, which resulted in the loss of the survey reference monument. However, a comparison of the June 28, 2001, and the May 4, 2002, survey measurements indicates a net gain of sediment at the site 18 well pad (fig. 13).

Well-pad sites 3 and 7 in the Harris Canyon area (figs. 3B and 3D) and sites 12 and 15 well pads in the Palluche Canyon area (figs. 4A and 4B) were adjacent to clay source areas. Only the June 28, 2001, and November 20, 2002, survey measurements are available for site 3 well-pad transects (fig. 14). Well-pad sites 3 and site 7 abut a weathered shale slope of about 35-percent grade. Transect 3PE is downslope from transect 3PW. Dam measurements and field observations following storm runoff at sites 3 and 7 indicate downslope transport of sediment from the hillslope and across the well pad. Transect survey measurements indicate transport across the well pad, especially at transect 3PW.

Net differences in land-surface elevation at transects 7PN and 7PS in the Harris Canyon area (fig. 3D) were small (fig. 15). At transect 7PN, the cross section was stable for all surveys. Exceptions were a slump deposition on the upslope end of the well pad and a tire rut near the center of the pad, both of which were absent by the May 2002 survey (not shown). Land-surface elevation changed little between May and November 2002. At transect 7PS, sediment deposition was equivalent to about a 3-in. increase in land-surface elevation across the transect between June 2001 and May 2002 (not shown). This 3-in. increase had largely disappeared by November 2002, resulting in a minor difference in land-surface elevation compared with the original 2001 survey.

Data collected for well-pad transects 12PN and 12PS (figs. 4A and 4B; fig. 16) in the Palluche Canyon area indicate sediment erosion near the upslope edge of the pad and redeposition on the well pad. Measurements for well-pad transects 15PE and 15PW (fig. 4A) in the Palluche Canyon area indicate erosion and redeposition at the upslope edge of the well pad and, in general, erosion near the downslope edge of the well pad (fig. 17).

Field Observations

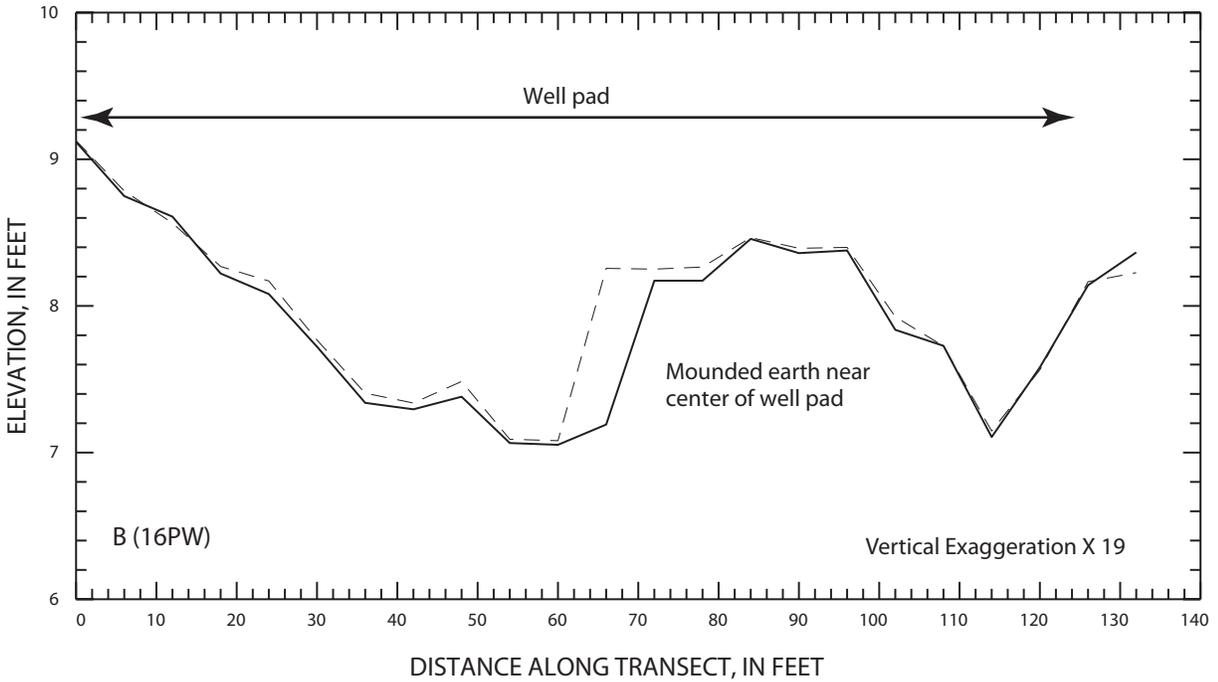
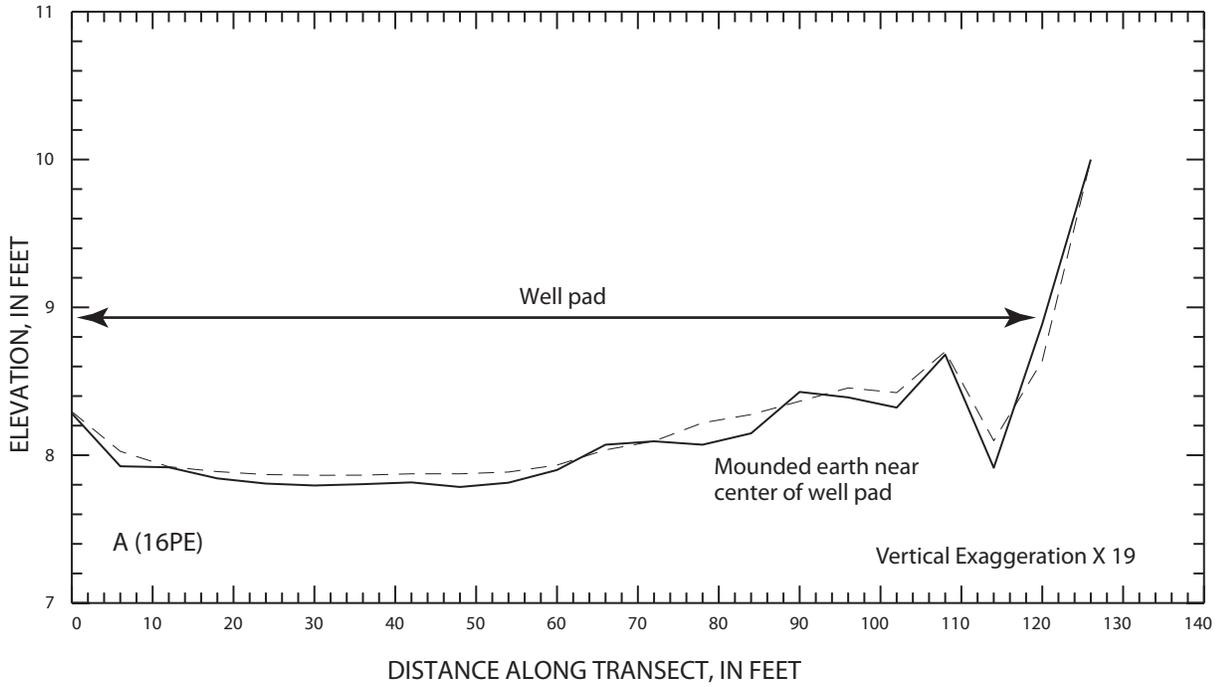
To draw meaningful conclusions, data obtained through measurements at point locations need to be generalized over a broad spatial area. Erosion in an arid landscape, however, is not a spatially generalized process but is focused at point locations that are a function of any of several variables interacting in complex ways that can focus energy and increase erosion potential. These variables include slope, cohesiveness of source material, elevation differences between points in the drainage area, vegetative cover, and the proximity of these variables to each other and to the point of measurement. For this reason, field observations, although not quantitative, can be valuable for understanding processes and interactions on the landscape. Some of the observed processes were quite dramatic, such as focused bank erosion (fig. 18), whereas other processes, such as sediment-color differences that show sediment-transport patterns, are more subtle. Field observations can elucidate processes not well captured by point measurements. The following discussion of field observations focuses on roads aligned generally parallel to topographic contour, roads that cross topographic contour, and well pads.

Roads Parallel to Topographic Contour

Dams on hillslopes upslope from roads at sites 3, 4, and 9 in the Harris Canyon area (figs. 3B and 3F) accumulated sediment transported from nearby shale and siltstone source areas (figs. 19 and 20), whereas dams at sites 8 (fig. 21) and 6 in the Harris Canyon area accumulated sediment transported from sandy hillslopes. Despite the differences in source rock material, observations at these sites indicate that both sandstone and siltstone weather to provide an abundant sediment supply. In the Harris Canyon area and in the flatter, more open Palluche Canyon area, bedrock, where it composes a large percentage of the drainage area, forms an impermeable surface that can contribute large volumes of runoff and increase the sediment-transport potential of runoff entering a dam.

Color differences between sediments derived from sandy and shaley and silty source areas clearly delineated surface-runoff flow lines. In the narrower canyons in the Harris Canyon area and in the flatter and broader canyons in the Palluche Canyon area, sediment was transported from the surrounding land and deposited on the road surface by runoff. Differences in sediment color indicate that some of the greenish sediment trapped by dam 1A originated from a shale and siltstone source area at the base of the canyon wall and was transported across the road to the dam (fig. 22). Transverse erosion across the road surface, evident in figure 22, indicates a sediment contribution from upslope of the road. Prior to the large rainfall in 2002, sediment from upslope of the road was captured by the road berm on the upslope right side of the road.

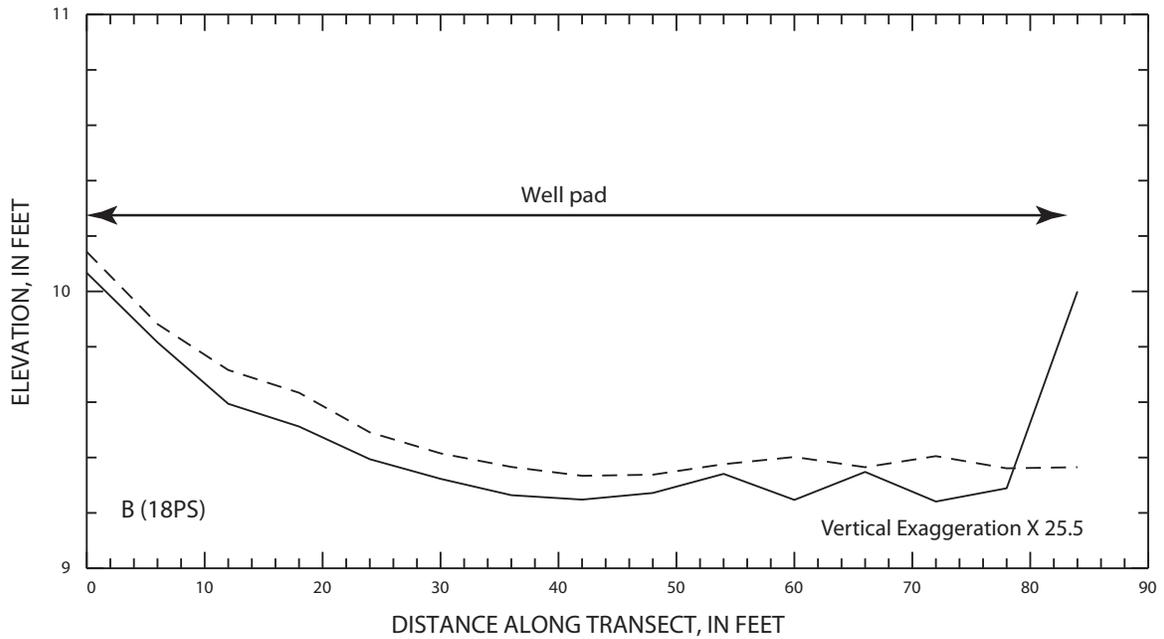
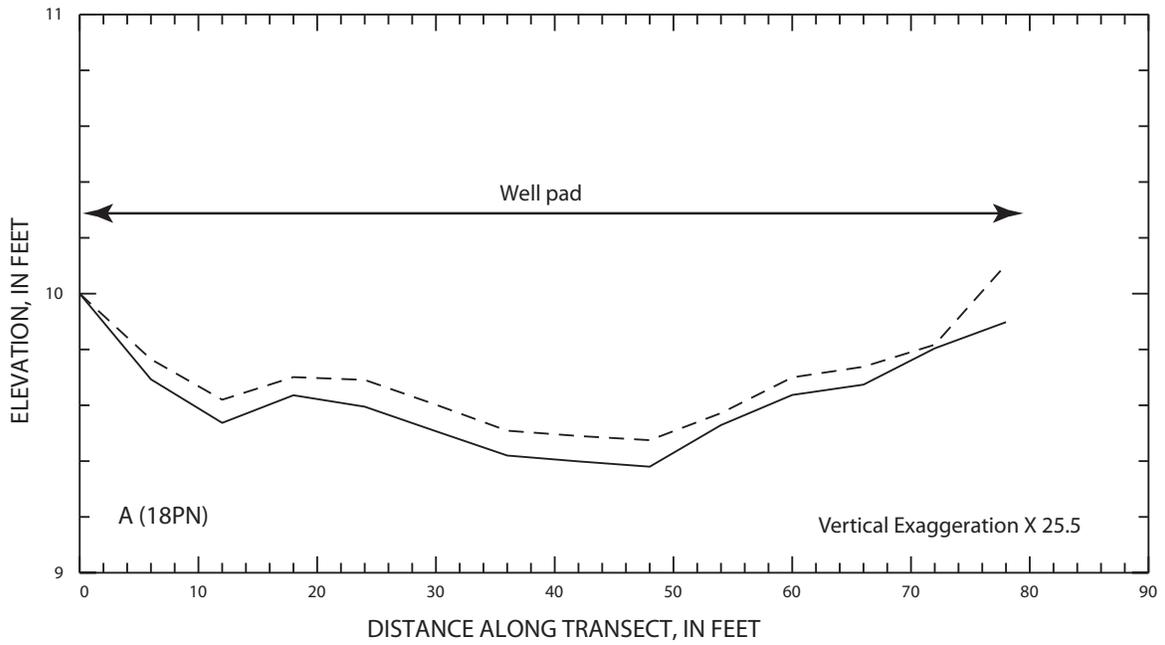
Unlike at sites at which bedrock was part of the contributing area, the drainage at the site 14 dam in the Palluche Canyon area was well defined, collecting runoff primarily from the road



EXPLANATION

- Elevation along transect, June 28, 2001
- - - Elevation along transect, November 20, 2002

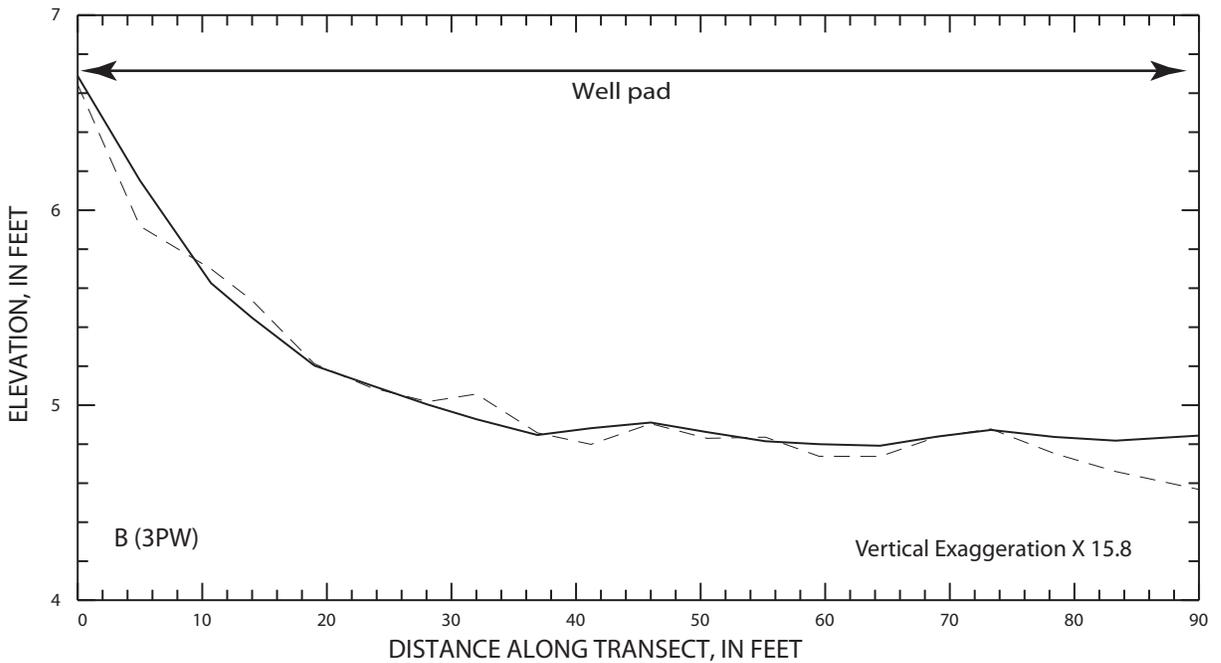
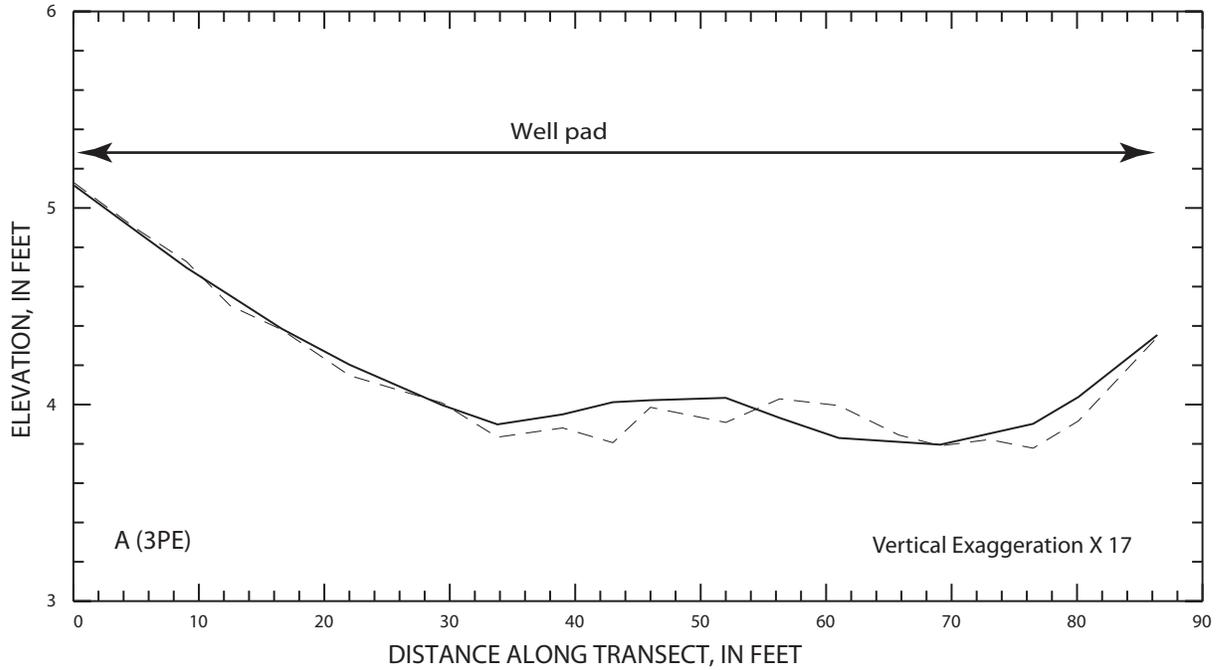
Figure 12. Land-surface changes for transects (A) 16PE and (B) 16PW in the Palluche Canyon area, June 28, 2001–November 20, 2002. Location of site 16 shown in figure 4A. View is to the northwest.



EXPLANATION

- Elevation along transect, June 28, 2001
- - - Elevation along transect, November 20, 2002

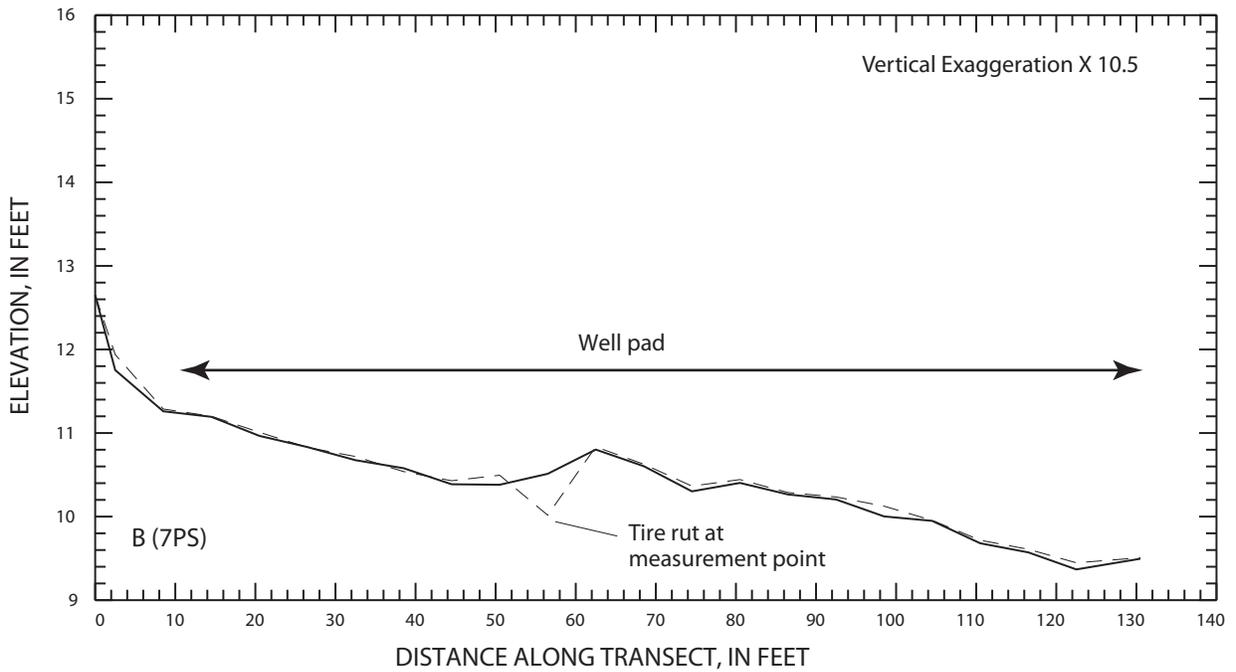
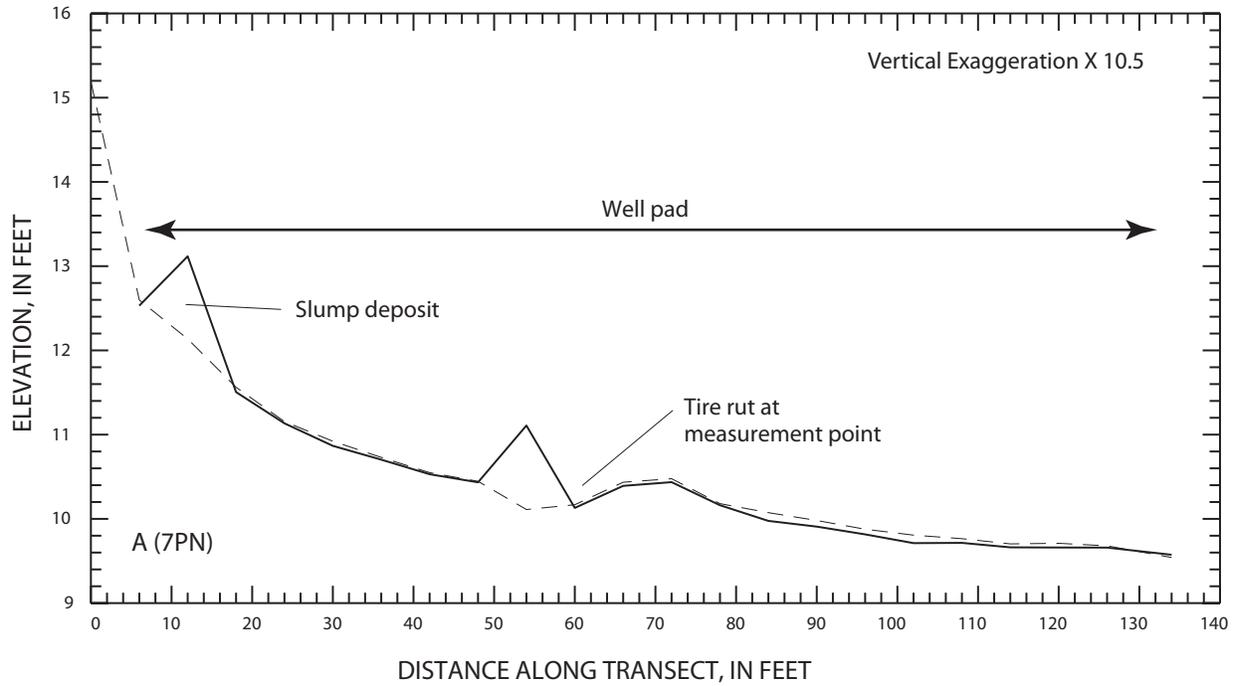
Figure 13. Land-surface changes for transects (A) 18PN and (B) 18PS in the Palluche Canyon area, June 28, 2001–May 4, 2002. Location of site 18 shown in figure 4A. View is to the south.



EXPLANATION

- Elevation along transect, June 28, 2001
- - - Elevation along transect, November 20, 2002

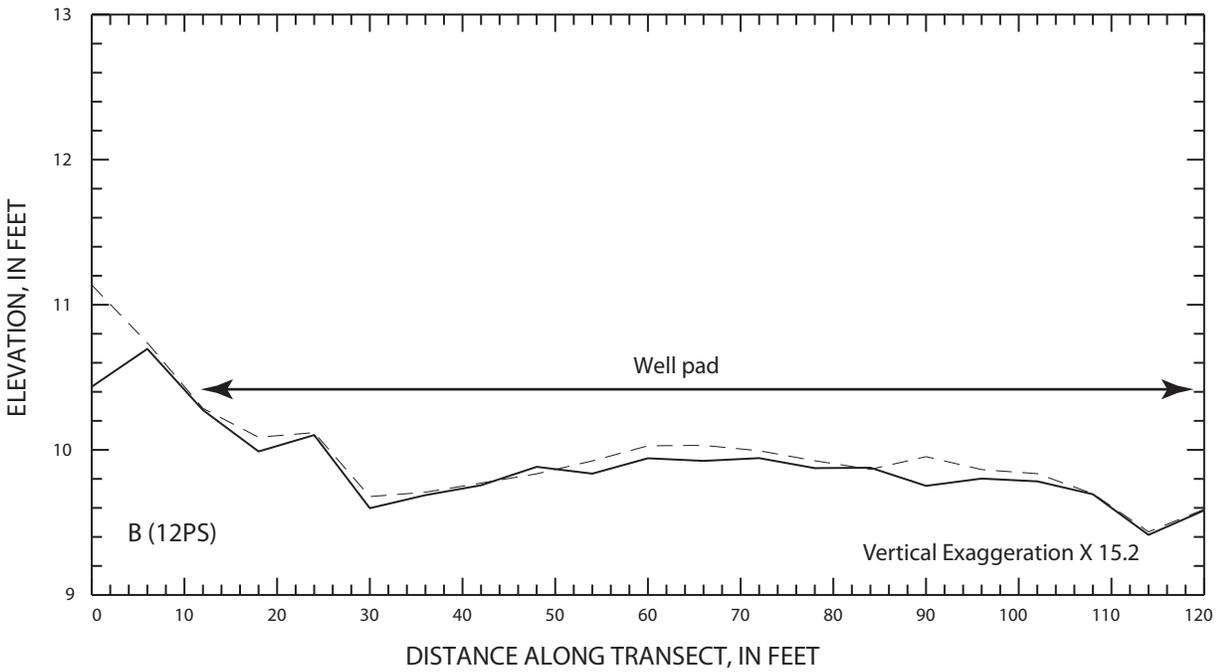
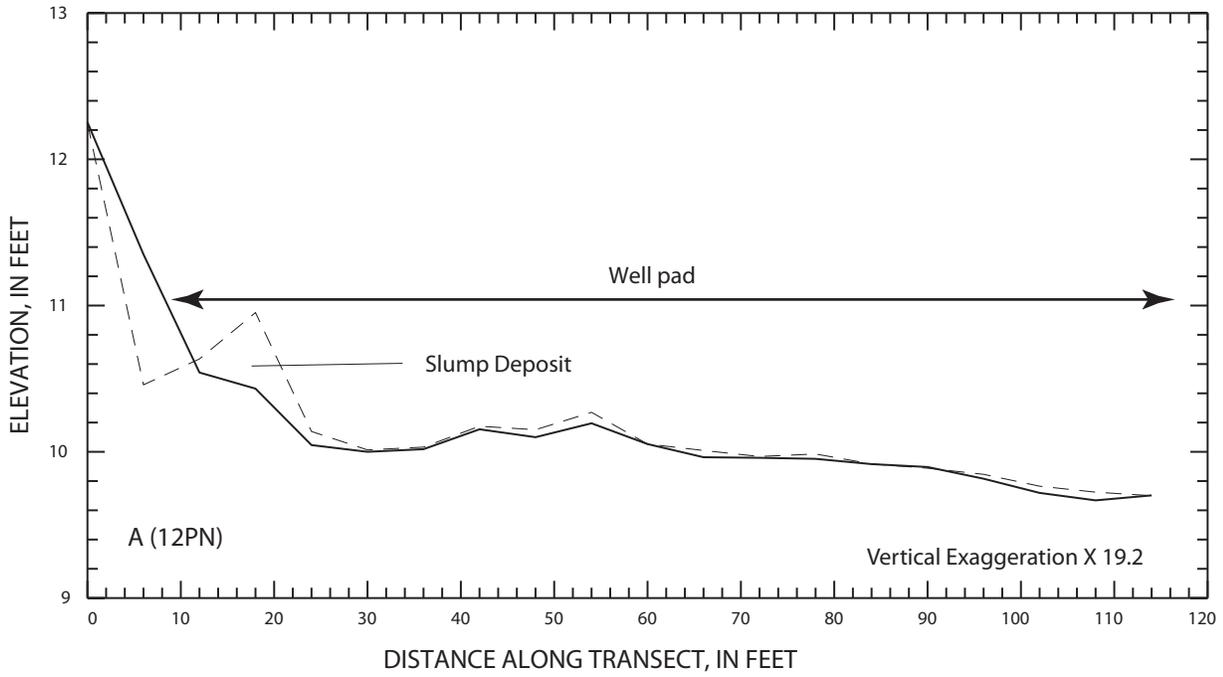
Figure 14. Land-surface changes for transects (A) 3PE and (B) 3PW in the Palluche Canyon area, June 28, 2001–November 20, 2002. Transect locations shown in figure 4A. View is to the west.



EXPLANATION

- Elevation along transect, June 28, 2001
- - - Elevation along transect, November 20, 2002

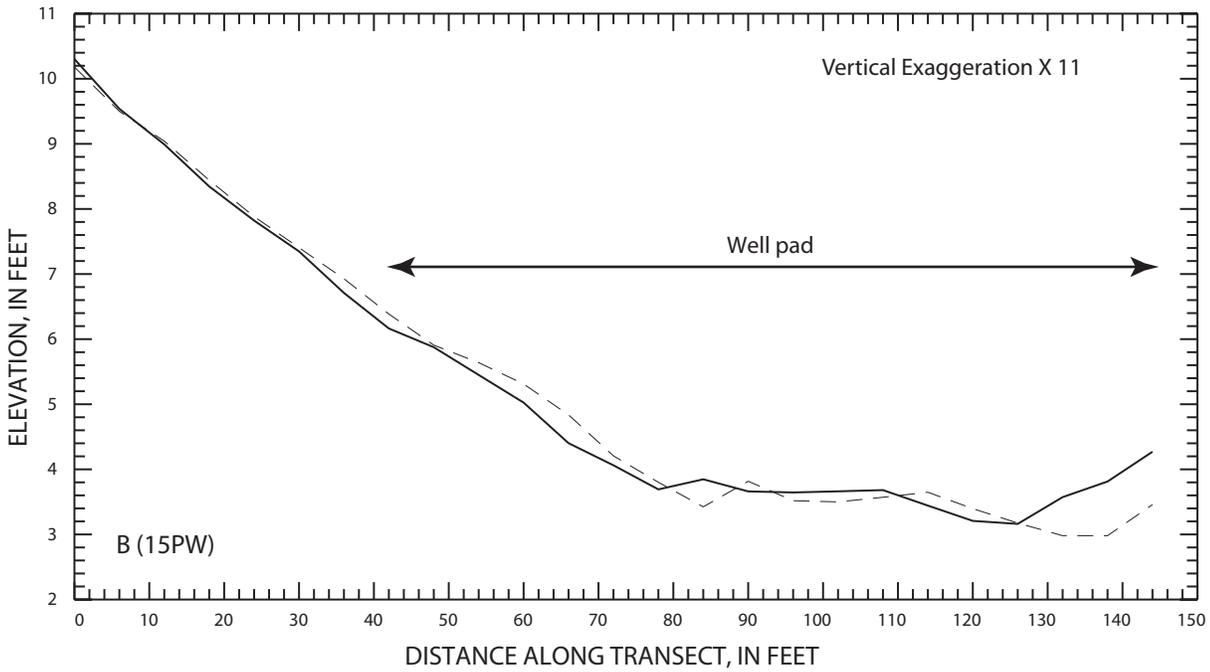
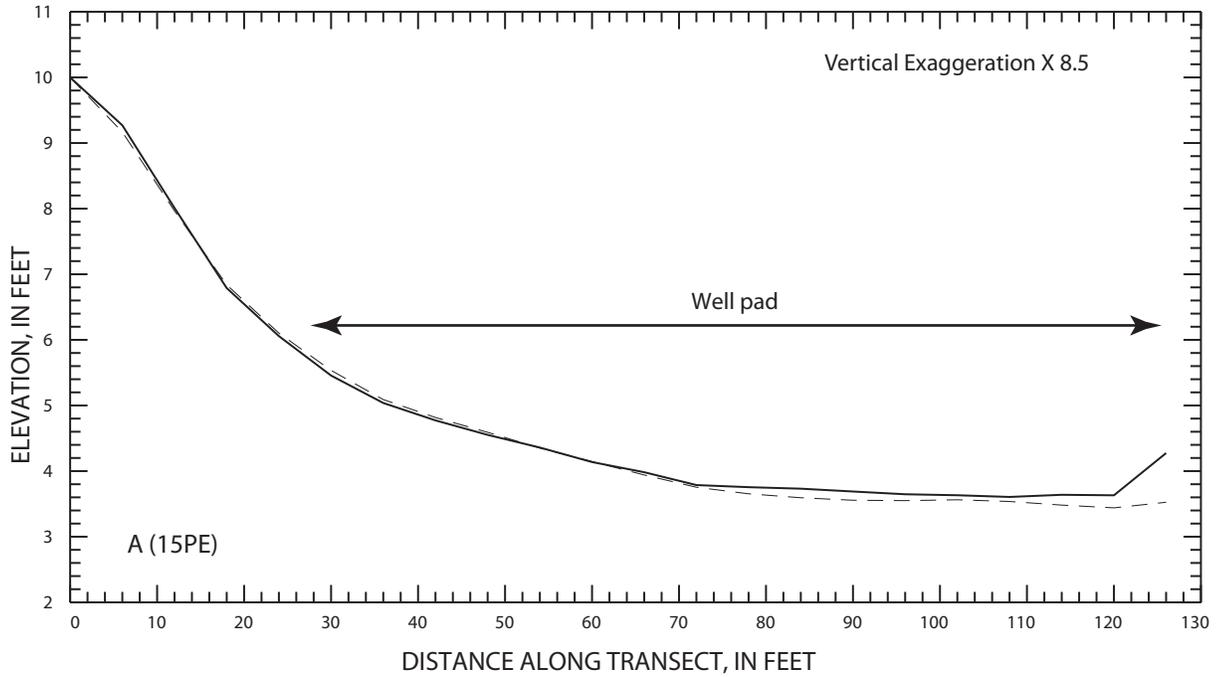
Figure 15. Land-surface changes for transects (A) 7PN and (B) 7PS in the Harris Canyon area, June 28, 2001–November 20, 2002. Transect locations shown in figure 3D. View is to the south.



EXPLANATION

- Elevation along transect, June 28, 2001
- - - Elevation along transect, November 20, 2002

Figure 16. Land-surface changes for transects (A) 12PN and (B) 12PS in the Palluche Canyon area, June 28, 2001–November 20, 2002. Transect locations shown in figure 4B. View is to the south.



EXPLANATION

- Elevation along transect, June 28, 2001
- - - Elevation along transect, November 20, 2002

Figure 17. Land-surface changes for transects (A) 12PN and (B) 12PS in the Palluche Canyon area, June 28, 2001–November 20, 2002. Transect locations shown in figure 4B. View is to the south.



Figure 18. Truck on road above area of focused bank erosion. Note the fence posts hanging from fence wire. Road is near site 9, Harris Canyon area. View is to the northeast.

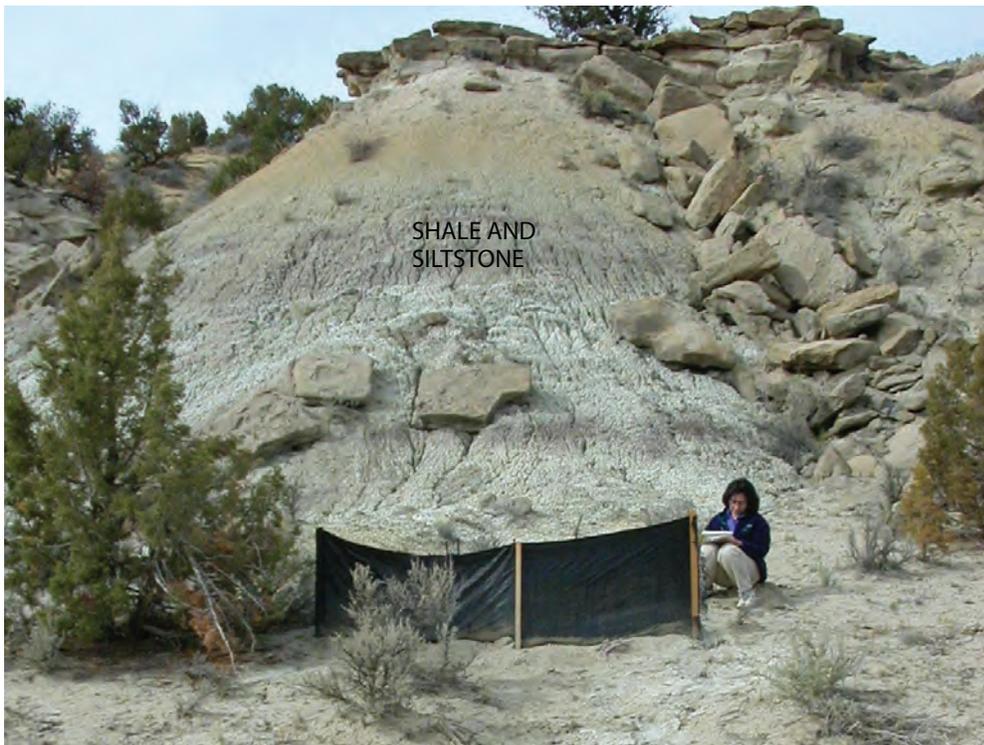


Figure 19. Sediment dam 9D and weathered shale and siltstone in the drainage contributing area, Harris Canyon area. Location of dam 9D shown in figure 3F. View is to the northwest.

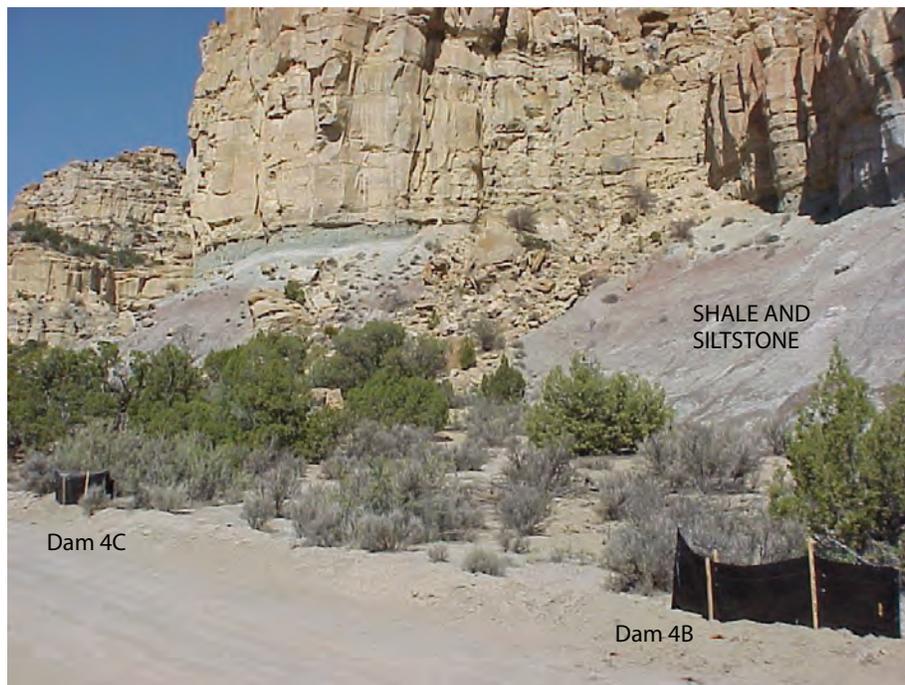


Figure 20. Weathered shale and siltstone in drainage contributing areas of sediment dams 4B and 4C in the Harris Canyon area. Locations of dams 4B and 4C shown in figure 3B. View is to the northwest.



Figure 21. Areas (indicated by arrows) where headcuts in the upslope road berm near sediment dams 8A and 8C have extended beyond the road berm and up the hillslope, Harris Canyon area. Locations of dams 8A and 8C shown in figure 3E. View is to the northwest.



Figure 22. Color of sediment on road near sediment dam 1A indicating source of runoff as the weathered shale and siltstone (shown in the upper right of photograph), Harris Canyon area. Locations of dams 1A and 1B shown in figure 3B. View is to the west.

surface. Site 14 differed from sites in the northern part of the study area and is characterized by a flatter surrounding terrain and a greater distance to the bedrock cliffs. The road at site 14 (fig. 4A) appeared to be fed more diffusely than the road in the steeper canyons with occasional flow focused by plant roots onto the road, but much of the runoff remained confined on the hillslope side of the road berm.

At sites where land on either side of the road was flat, there commonly was evidence of flow and sediment transport across land surface for a distance of several feet without downcutting or rill formation. The road berm sometimes acted as a dam, trapping sediment above the road (fig. 23). However, higher intensity rainfall caused sheet-flow runoff, transporting sediment over the berm onto the road. Lower intensity rainfall transported sediment by focused flow, entering the road through 2- to 3-in.-wide headcuts in the road berms (fig. 23). For roads parallel to contour, road-berm headcuts generally were focused on the upslope side of the roadbed, with a range of 15-65 headcuts per 100 ft of road on the upslope side and 0-2 headcuts per 100 ft of road on the downslope side (table 4).

At many locations, road-berm cuts reached only a few tenths of a foot headward from the road berm and were fed by downward movement of sediment from the area upslope from the cut (fig. 23). Some cuts, however, were observed to have eroded headward for several feet, forming a distinct channel (fig. 21). The principal input of runoff to roads parallel to contour was focused by established rills or channels on the adjacent

hillslopes. Where the road intersected a pre-existing drainage, runoff flowed directly across the road and exited on the downslope side of the road (fig. 24), usually after transport of a few to several hundred feet along the road itself.

Most of the locations at which dams could be placed to trap sediment draining from roads were selected because they were established drainage channels (fig. 24). For rainfall of smaller magnitude and intensity these dams worked well, but rainfall of larger magnitude and intensity (large enough to integrate flow paths in the entire drainage area) generated large volumes of runoff that overwhelmed the capacity of these dams (fig. 25), caused erosion along the sides and back of the dam, and contributed to deepening of the channel below the road. The erosive force associated with large magnitude and intensity runoff was at times sufficient to erode the downslope edge of the road surface. During one rainfall, focused flow through the dam caused development of a channel below the road that was not present when the dam was established. No erosion rates were estimated for the larger runoff events that breached dams.

Based on observations, roads aligned parallel to contour facilitate erosional processes in two ways: (1) roads cut across and collect runoff from previously established drainages and (2) roads, where cut into hillsides or into the land surface, provide focal points for the initiation of erosion. In the first process, runoff and sediment from pre-existing small drainages may be



Figure 23. Mud cracks (in upper left of photograph) as evidence of ponding and sediment deposition behind the road berm at site 4. Headcuts, formed in the road berm where runoff overflowed the berm, do not extend upslope from berm. Pen in middle foreground for scale. Near site 4 in the Harris Canyon area.

Table 4. Number of cuts in upslope and downslope road berms, for road parallel to contour.

Nearby sediment dam or transects (figs. 3 and 4)	Soil composition	Length of road examined, in feet	Number of cuts in berm / number of cuts per 100 feet of road	
			Upslope side of road	Downslope side of road
1A-B	Silty sand	200	65 / 32.5	0 / 0
4A-C	Silty sand	148	23 / 15.5	2 / 1.4
3G-F	Silty sand	200	47 / 23.5	20 / 10
8A-C	Sand	400	37 / 9.3	2 / 0.5
5RW-5RE	Sand	400	46 / 11.5	0 / 0
9A-B	Silty sand	180	15 / 8.3	1 / 0.6
9C-E	Silty sand	242	37 / 15.3	1 / 0.4
9F-G	Silty sand	76	3 / 3.9	3 / 3.9
13A-B	Silty sand	289	29 / 10.0	1 / 0.3
14A-B	Sand	200	20 / 10.0	38 / 19.0
Average number of cuts in berm per 100 feet of road			14	3.6



Figure 24. Sediment dam 3F installed at the downslope edge of a road on a pre-existing drainage in the Harris Canyon area. The channel deepened and widened, with concurrent deterioration of the road edge, over the 2-year course of this study. Location of dam 3F shown in figure 3B. View is to the south.



Figure 25. Sediment dam 9A overwhelmed by high runoff and partially buried in transported sediment. Location of dam 9A, in the Harris Canyon area, shown in figure 3F. View is to the east.

intercepted by and transported along the road (figs. 3E and 3F) to an outlet point (fig. 21, dam 8A; fig. 25, dam 9A). The outlet point may be a new or pre-existing drainage at some distance down the road from the numerous small drainages contributing runoff to the road. Sediment is deposited on the road from accumulated runoff originating from a segment of the hillslope. This accumulated runoff and sediment are channeled by the road bed to a single outlet point on the downslope side of the road (figs. 21 and 25). Because flow from the hillslope drainages is concentrated into a larger flow along the road, the potential erosive capacity of the runoff is magnified, the degree of magnification depending on the slope and topography at the point. The second way in which roads facilitate erosional processes is in providing focal points for the initiation of erosion on freshly exposed or disturbed surfaces. Road berms, created when level roads are cut into hillslopes, provide oversteepened slopes on which enough potential energy is available to initiate headcut erosion during runoff. Headcut erosion occurs naturally on weathered surfaces where rills form at slope breaks and erode headward. Periodic grading of the roads sustains the heights of the berms and maintains the potential energy needed to initiate rill formation and headcut erosion. In contrast to roads adjacent to hillslopes, roads through flatter landscapes, such as parts of the Palluche Canyon area, show little evidence of headcut erosion extending upslope from road berms.

Roads Across Topographic Contour

Roads across topographic contour generally are well-pad access roads or roads that cross drainage divides and can serve to integrate parts of the watershed as a secondary drainage network; however, roads across topographic contour constitute a small percentage of the road network. Although no sediment dams were installed on across-contour roads, depositional features, such as splay deposits formed where roads across contour intersect roads parallel to contour (fig. 26), indicate that roads across contour serve as downslope conduits for sediment transport.

Well Pads

Base material at well-pad sites 2 and 5 (figs. 3B and 3C) was primarily sandy, whereas base material at well-pad sites 3, 7, and 12 (figs. 3B, 3D, and 4B) was primarily silty. Well pads typically were flat surfaces cut into the adjacent hillslope. Because the pads were wider than the roads, the upslope cut face and downslope berm generally were much higher than road berms. Areas upslope from well pads supplied sediment to the well pad, and sometimes fan deposits formed at the base of the well-pad berm (fig. 27). Dams below the downslope well-pad berm trapped sediment mainly from the well-pad slope itself; drainages developed over time at some places and captured runoff from the well-pad surface (fig. 28). Like roads, well pads can provide conditions for focusing runoff and locally increasing erosion. At site 3, a 4-ft-deep channel was cut between the

embankment surrounding the well pad and the cliff face, where runoff from the mesa was focused at this point. At site 12, a similar focus of runoff from the hillslope by an embankment stabilizing the well pad led to development of a deep channel incised into the road (fig. 29).

Processes of Upland Erosion

As studies in forested humid temperate watersheds have shown, unpaved roads are considered a major source of sediment in undeveloped areas, serving both as sources of sediment and as conduits for transporting accumulated sediment out of the basin of origin. In these humid temperate areas, which have a ground cover of litter and duff, roads and associated road cuts constitute a substantial percentage of total open and bare ground. By contrast, canyons dissecting sandstone and shale characterize the Largo Canyon watershed, and much of the land surface is unvegetated ground interspersed with shrubs or rock. The area of bare land surface constituted by roads is relatively small compared with the area of bare and easily erodible landscape.

Northwest New Mexico represents a different climate and landscape than that in which the observations about the role of roads in landscape erosion were developed. In arid climates, extreme runoff events shape the landscape and do most of the work of transporting sediment (Graf, 1998). The effects of extreme runoff events remain evident in the subsequent configuration of the landscape; subsequent, milder runoff events do not account for the existing configuration of the landscape. Even if, in the arid Largo Canyon watershed, roads do play an important role in landscape erosion, the mechanisms by which roads contribute to erosion in arid climates would be expected to differ from those in humid, temperate forested climates because erosion processes reflect the climate and landscape in which they occur.

Roads across contour can serve as a downslope conduit for runoff and transported sediment but constitute a small percentage of total road area. Roads constructed parallel to contour can minimize erosion potential compared with roads constructed across contour. Roads parallel to contour, however, contribute to erosion by more indirect processes in two ways: (1) initiating headcut erosion at the upslope road berm and (2) concentrating small inflows upslope into a larger flow with increased erosion potential at the downslope road berm. Variations of this conceptual model are a function of slope, orientation to contour, and position with respect to other landscape features.

On the upslope side of roads parallel to contour, weathered shale slopes were observed to develop more extensive rill networks than did weathered sandstone slopes. For a given source material, steepness of the adjacent topography and proximity to a cliff or mesa determines the degree of rill or channel formation and runoff accumulation onto the land surface. The upslope roadside berm acts as a dam for low runoff events and when adjacent topography is relatively flat compared to the hillslope, accumulating eroded sediment upslope from the road surface.



Figure 26. Splay deposit, formed from sediment transported along across-contour road and subsequently eroded by runoff, forms the curved cut in berm of parallel-contour road. Across-contour road connects from lower left of photograph, Harris Canyon area. View is to the southwest.



Figure 27. Sediment erosion from upslope pad berm near sediment dam 2C redeposited on the pad, partially burying oil and gas industry equipment. Location of dam 2C in Harris Canyon area is shown on figure 3B. View is to the southwest.



Figure 28. Sediment dam 5A and headcuts eroded into downslope pad berm. Headward erosion has extended the headcuts up onto the surface of the well pad. Transect 5PNE whisker flagging crosses the well pad behind author and in front of vehicle (arrow points along transect). Location of dam 5A in Harris Canyon area shown in figure 3C. View is to the northwest.



Figure 29. Author standing in a channel cut by focused runoff near site 12 in the Palluche Canyon area. Location of site 12 shown in figure 4B. View is to the southwest.

Headcuts initiated from road berms may subsequently release this sediment from temporary storage. The number of established rills and drainage networks that may cross the road and continue downslope on the other side is greater on steeper hillslopes or outcrops.

On the downslope side of a road parallel to contour, accumulated runoff from the adjacent hillslope concentrates and discharges to an existing or newly formed gully or arroyo. The degree of downcutting depends on the elevation difference between the road and the gully or arroyo. Deep channels were observed cutting headward into the roadbed where an arroyo was more than 10 feet below the road. Where roads were of low grade along the valley axis or downslope across contour, the road served more as a conduit for runoff.

Well pads function in the erosion process in a way similar to roads parallel to contour by providing opportunities for headcut erosion or focusing of flow. Erosion rates for well pads are greater than for roads, but the total area of well pads is much smaller than that of roads, so the overall contribution to total sediment erosion is smaller. Where the construction of a well pad focuses runoff from bedrock portions of the drainage area, well pads can contribute to dramatic local erosion (figs. 27 and 29). Transect surveys of well pads indicate small net sediment losses and gains and a consistent downslope movement of sediment by erosion and redeposition. Redeposition of sediment probably heals many small, newly formed rills and may explain the general lack of permanent rill development upslope from the well pads and road berms because the redeposition indicates that runoff and sediment movement are large enough to successively form and heal rills.

Summary

Largo Canyon, located in the San Juan Basin of northwestern New Mexico, is one of the longest dry washes in the world. Largo Canyon drains an area of 1,700 mi². The head of Largo Canyon is on the western slope of the Continental Divide. The regional topography is composed of sandstone-capped mesas dissected by deep, narrow canyons and arroyos. Weathering of shale and sandstone results in a highly erodible landscape and an abundant sediment supply.

Oil and gas production in the San Juan Basin has required the development of an extensive network of dirt roads to service the oil and gas wells. Presently, there are about eight wells per square mile; the density of wells is expected to increase. Potential environmental effects on landscape stability that may result from construction of additional oil- and gas-well service roads and well pads have not been documented.

The Harris Canyon road- and well-pad analysis area contains 108 well pads with a combined area of 0.1 mi², or 64.5 acres, and 84 miles of road with a road density of 2.5 mi/mi². The Palluche Canyon road- and well-pad analysis area contains 114 well pads with a combined area of 0.04 mi², or 28.8 acres, and 114 miles of roads with a road density of 2.2 mi/mi².

Sediment dams were installed at 43 sites: 21 on hillsides upslope from roads or pads, 11 at the downslope edges of roads, and 11 at the downslope edges of well pads to measure hillslope, road and well-pad erosion. Data from 26 dams were used in the analysis. Erosion of roads and well pads was measured directly using repeated surveys of monumented survey transects. Measurements of sediment accumulation behind 26 dams, recorded at 4- to 6-week measurement intervals, indicate that average erosion rates at the dams significantly correlate to size of the contributing drainage area, and the average erosion rate is significantly different for dams in certain landscape positions. The average erosion rate normalized by drainage area was about 0.001 ft/yr below roads, 0.003 ft/yr on the hillslopes, and 0.011 ft/yr below well pads.

Results of a two-sample t-test indicated that for dams located at the downslope edges of well pads, average erosion rates were significantly larger than for dams below roads and on hillslopes. No significant difference in average erosion rate was indicated, however, for dams below roads compared with dams located on hillslopes.

Sediment-accumulation data for measurement intervals over which dams were breached during 2002, resulting from the large volume of runoff generated by high-intensity storms, were not used to compute erosion rates. For this reason, the higher range of erosion rates is underrepresented and the results are biased toward the lower end of the range of erosion rates in this study.

Measurements along road transects generally indicate that sediment is eroded from the top of road berms and redeposited at the base of the berms and may be transported downslope along the road. Measurements along well-pad transects generally indicate that sediment eroded from hillslopes is transported over the surface of the well pad and down the well-pad edges.

Based on field observations, roads aligned parallel to contour facilitate erosional processes in two ways: (1) roads cut across and collect runoff from previously established drainages and (2) roads, where they are cut into hillsides or into the land surface, provide focal points for the initiation of erosion. Runoff and sediment from pre-existing small drainages may be intercepted by and transported along the road to an outlet point where the potential erosive capacity of the runoff is magnified by the accumulation of runoff. Roads also facilitate erosional processes by providing focal points along road berms for the initiation of headcut erosion. Periodic grading of roads maintains the heights of the berms and the potential energy conditions needed to initiate rill formation and headcut erosion.

Across-contour roads can serve as conduits for sediment transport, but constitute a small percentage of the road network. Well-pad berms generally were much higher than road berms, and fan deposits were observed to form at the base of some upslope well-pad berms. Dams below the downslope side of well pads trapped sediment mainly from the well-pad slope itself, with drainages sometimes developing over time to capture runoff from the well-pad surface. Like roads, well pads can provide conditions for focusing runoff and locally increasing erosion.

Well pads function in the erosion process in a way similar to roads parallel to contour by providing areas for headcut erosion or focusing of flow. Erosion rates for well pads are greater than for roads, but the total area of well pads is much smaller than that of roads, so the overall contribution to total sediment erosion from well pads is smaller.

References

- Anderson, D.M., and MacDonald, L.H., 1998, Modelling road surface sediment production using a vector geographic information system: *Earth Surface Processes and Landforms*, v. 23, p. 95-107.
- Best, D.W., Kelsey, H.M., Hagans, D.K., and Alpert, M., 1995, Role of fluvial hillslope erosion and road construction in the sediment budget of Garrett Creek, Humboldt County, California: U.S. Geological Survey Professional Paper 1454-M, 9 p.
- Brister, B.S., and Hoffman, G.K., 2002, Fundamental geology of San Juan Basin energy resources *in* New Mexico's Energy, Present and Future: New Mexico Bureau of Geology and Mineral Resources Decision-Makers Conference 2002, San Juan Basin, p. 20-25.
- Bureau of Land Management, 2003, Farmington Resource Management Plan with Record of Decision: U.S. Department of the Interior, Bureau of Land Management, Farmington Field Office, Farmington, New Mexico, 148 p.
- Croke, J., Hairsine, P., and Fogarty, P., 1999, Sediment transport, redistribution and storage on logged forest hillslopes in south-eastern Australia: *Hydrological Processes*, v. 13, p. 2705-2720.
- Dane C.H., and Bachman, G.O., 1965, Geologic Map of New Mexico: U.S. Geological Survey, 1 sheet, scale 1:500,000.
- Dick-Peddie, W.A., 1993, New Mexico Vegetation -Past, Present, and Future: Albuquerque, New Mexico, University of New Mexico Press, 244 p.
- Dunne, T., and Dietrich, W., 1982, Sediment sources in tropical drainage basins, *in* Soil erosion and conservation in the tropics: American Society of Agronomy and Soil Society of America, p. 41-55.
- Gellis, A.C., 1996, Gullyng at the Petroglyph National Monument, New Mexico: *Journal of Soil and Water Conservation*, v. 51, no. 2, p. 155-159.
- Golden Software, Inc., 2002, Surfer 8 user's guide: Golden, Colo., Golden Software, Inc., 640 p.
- Graf, W.L., 1998, Fluvial processes in dryland rivers: Caldwell, N.J., The Blackburn Press, 346 p. (reprinted 2002).
- Grayson, R.B., Haydon, S.R., Jaysuriya, M.D.A., and Finlayson, B.L., 1993, Water quality in mountain ash forests-Separating the impacts of roads from those of logging operations: *Journal of Hydrology*, v. 150, p. 459-480.
- Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 5, Chap. C1, 59 p.
- MacDonald, L.H., Anderson, D.M., and Dietrich, W.E., 1997, Paradise threatened-Land use and erosion on St. John, U.S. Virgin Islands: *Environmental Management*, v. 21, no. 6, p. 851-863.
- Megahan, W.F., 1974, Erosion over time on severely disturbed granitic soils-A model: USDA Forest Service Research Paper INT-156, 14 p.
- Megahan, W.F., 1983, Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho: *Water Resources Research*, v. 19, no. 3, p. 811-819.
- Megahan, W.F., Wilson, M., and Monsen, S.B., 2001, Sediment production from granitic cut-slopes on forest roads in Idaho, USA: *Earth Surface Processes and Landforms*, v. 26, p. 153-163.
- Minitab, Inc., 2003, MINITAB Statistical Software, Release 14 for Windows: State College, Pennsylvania.
- Montgomery, D.R., 1994, Road surface drainage, channel initiation, and slope instability: *Water Resources Research*, v. 30, no. 6, p. 1925-1932.
- Mosley, M.P., 1980, The impact of forest road erosion in the Dart Valley, Nelson: *New Zealand Journal of Forestry*, v. 25, no. 2, p. 184-198.
- Motha, J.A., Wallbrink, P.J., Hairsine, P.B., and Grayson, R.B., 2003, Determining the sources of suspended sediment in a forested catchment in southeastern Australia: *Water Resources Research*, v. 39, no. 3, p. ESG 2-1 to ESG 2-14.
- Motha, J.A., Wallbrink, P.J., Hairsine, P.B., and Grayson, R.B., 2004, Unsealed roads as suspended sediment sources in an agricultural catchment in south-eastern Australia: *Journal of Hydrology*, v. 286, p. 1-18.
- Reid, K.D., Wilcox, B.P., Breshears, D.D., and MacDonald, L., 1999, Runoff and erosion in a piñon-juniper woodland-Influence of vegetation patches: *Soil Science Society of America Journal*, v. 63, no. 6, p. 1869-1879.
- Western Region Climate Center, 2004, New Mexico climate summaries: Desert Research Institute, accessed June 14, 2004, at URL <http://www.wrcc.dri.edu/summary/climsnm.html>.
- Ziegler, A.D., and Giambelluca, T.W., 1997, Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand: *Journal of Hydrology*, v. 196, p. 204-229.
- Ziegler, A.D., Sutherland, R.A., and Giambelluca, T.W., 2000, Runoff generation and sediment production on unpaved roads, footpaths, and agricultural land surfaces in northern Thailand: *Earth Surface Processes and Landforms*, v. 25, p. 519-534.