SEDIMENT TRANSPORT AND STORAGE IN NORTH FORK CASPAR CREEK, MENDOCINO COUNTY, CALIFORNIA: WATER YEARS 1980-1988

by

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ABSTRACT

Sediment Transport and Storage in North Fork Caspar Creek,

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The old-growth redwood forest of North Fork Caspar Creek was clear-cut. between 1864 and 1904. Previous research on logging-related changes in suspended sediment and streamflow would suggest that North Fork Caspar Creek has recovered from historical logging (Rice et al., 1979; Ziemer, 1981); research on the influence of large woody debris (LWD) on channel form and function would suggest it has not (Sedell and Luchessa, 1982; Keller and Tally, 1979).

I developed a sediment budget for mainstem North Fork Caspar Creek for water years (WY) 1980-1988 to evaluate controls on sediment storage changes. Sediment budget findings, Caspar Creek logging history, and research on LWD were reviewed together to evaluate persistence of historical logging impacts.

During the study period, at least 70 percent of changes in sediment storage occurred at LWD jams, recent slidescars, and tributary junctions. Elsewhere, the streambed is well-armoured and net changes in sediment storage were slight. As of 1987, debris jams were near or at maximum storage capacity affording little prospect for attenuation of large-volume, sediment inputs. Over the study period, debris jam filling and LWD-

related bank erosion were roughly equivalent, and hence, the effect of LWD on the sediment budget was fairly neutral.

Average annual sediment yield for North Fork Caspar Creek during WY 1980-1988 was 69 tonnes/km^2, 9 tonnes per km^2 of which was bedload. This is comparable to estimates for other basins underlain by competent Franciscan terrane (Janda, 1972; Kelsey, 1980; Madej et al., 1986).

North Fork Caspar Creek may not have recovered from nineteenth-century logging. Comparison of LWD loading on North Fork Caspar Creek (24 kg/m^2) to similar streams in old-growth redwood basins (49 to 268 kg/m^2) and review of historical descriptions of log drives and channel preparation for drives, suggests that LWD loading and stability were greatly diminished by channel preparation for drives, the log drives themselves, and change to second-growth cover. These changes are significant, as LWD creates diverse habitat and provides long-term, large-volume sediment storage sites in old-growth streams (Keller et al., 1981). Extent and significance of impacts is unclear, however, because sufficiently detailed information describing historical channel conditions and fisheries is not available.

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CHAPTER 1: INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

The old-growth redwood forest of North Fork Caspar Creek was clear-cut between 1864 and 1904 (Appendix I: Logging History of Caspar Creek). During the summer of 1989 second growth logging was initiated on North Fork Caspar Creek (Figure 1) to evaluate the cumulative effects of logging. Previous research regarding logging-related changes in suspended sediment, turbidity, sediment yield, and streamflow would suggest that North Fork Caspar Creek has recovered from historical logging (Harr, 1976; Rice et al., 1979; Ziemer, 1981); however, research regarding the role of large woody debris in similar streams in old-growth redwood forest would suggest it has not (Keller and Tally, 1979; Keller et al., 1981).

In steep, gravel bed streams like North Fork Caspar Creek, large woody debris (LWD) exerts a significant influence on aquatic habitat diversity and provides long-term, large-volume sediment storage sites (Keller and Swanson, 1979). Persistence of adverse changes in the amount and stability of LWD, therefore, may cause significant adverse impacts to fisheries habitat conditions and sediment yield.

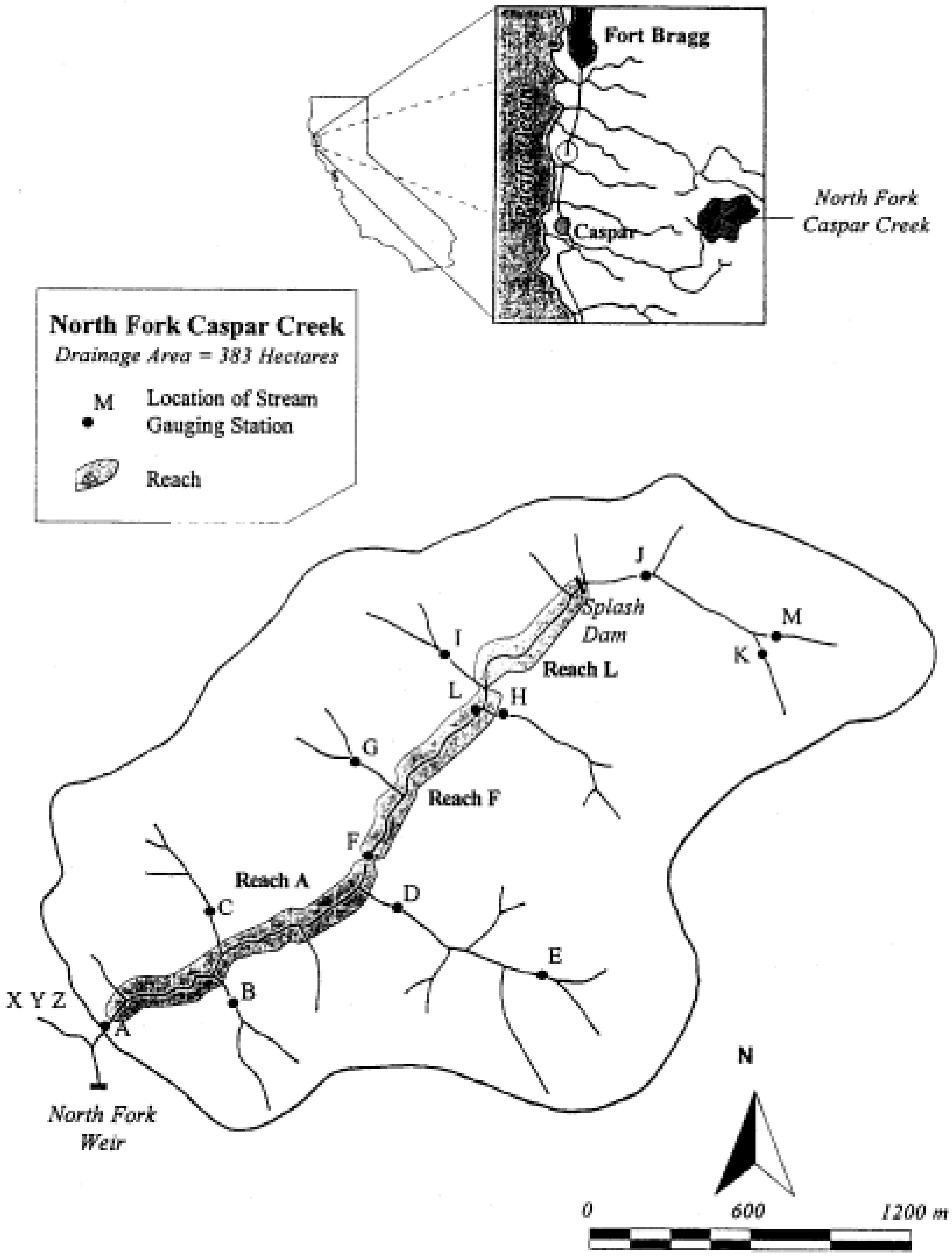

FIGURE 1. Location of North Fork Caspar Creek Study Area.

This study addresses two questions related to the potential impacts of historical and recent logging on North Fork Caspar Creek channel condition:

1) What were the processes controlling sediment production and channel storage changes just prior to second-growth logging (WY 1980-1988) - are channel processes and form indicative of recovery from historical logging?

2) Have historical logging activities and conversion to second-growth caused persistent changes in LWD loading and stability, channel morphology, and sediment yield?

To address these questions -

1) I developed a sediment budget for mainstem North Fork Caspar Creek for water years 1980-1988, the period just prior to second-growth logging, to determine the controls on sediment storage and channel changes;

2) I reviewed research describing the role of LVWD in streams draining old-growth redwood basins, together with historical data describing Caspar Creek logging, and field evidence for disturbance or removal of LWD to evaluate the persistence of historical logging impacts on LWD function.

1.2 MOTIVATION

Motivations for this study include:

1) to contribute to the understanding of how LWD influences channel form and sediment routing in steep, headwaters streams in mature, second-growth redwood forests;

2) to develop a pre-logging benchmark for comparison to post-logging condition in North Fork Caspar Creek and other similar streams; and

3) to contribute to the understanding of the impacts of present-day and historical logging activities on channel conditions in headwaters streams in the coastal redwood environment.

1.3 APPROACH

Analysis of WY 1980-1988 channel changes involved five sequential steps:

1) mapping of mainstem sediment storage (volume and distribution of sediment, vegetation age, depositional controls, frequency of erosion and transport, and source particle size distribution and bulk density);

2) definition of sediment storage reservoirs - grouping together landforms of similar source type (particle size distribution and bulk density) and relative mobility (frequency of erosion and transport);

3) estimation of mainstem channel storage changes from defined sediment storage reservoirs in terms of mass by particle size class (gravel, sand, fines);

4) estimation of watershed sediment yield in terms of mass by particle size class (gravel, sand, fines);

5) analysis of processes governing changes in channel form and storage, and watershed sediment yield.

Analysis of persistence of historical logging impacts involved four steps:

1) review of research regarding the role of LWD in streams draining old-growth coast redwood streams (Keller and Swanson, 1979; Keller et al., 1981);

2) review of research regarding factors controlling LWD loading and stability, and LWD loading data for old-growth and second-growth streams

(Keller et al., 1981) to choose an old-growth analog for North Fork Caspar Creek prior to nineteenth-century logging;

3) review of historical data describing logging and log drives in Caspar Creek, and literature describing methods used in northern California and the Pacific Northwest to "prepare" streams for log drives; and

4) evaluation of field evidence for disturbance or removal of LWD from North Fork Caspar Creek.

1.4 SITE DESCRIPTION AND PREVIOUS RESEARCH

Study Area Boundaries

The drainage area of North Fork Caspar Creek above the downstream boundary of the study reach is 3.8 km^2 (Figure 1). The study reach is 2400 meters long and extends from a partially collapsed splash dams downstream to gauging station A. The splash dam corresponds to a distinct change in mainstem channel and valley morphology. Upstream of the dam, the valley floor becomes significantly wider and more alluviated relative to reaches below the dam. Immediately downstream of station A and adjacent to the North Fork weir pond, tributaries X-Y-Z (drainage area = 1 km^2) join the mainstem channel. These tributaries were not included in the mainstem channel sediment routing study because they were clear-cut in 1985 and 1986, and a primary

[1]the splash dam was constructed to augment storm flows for nineteenth century log drives

objective of this study is to provide a description of mainstem channel prior to logging of the second growth forest in 1989. Lateral boundaries of the study area between gauging station A and the splash dam are defined by a distinct slope break where inner gorge slopes (commonly 70 percent or steeper) abut flat-lying valley fills and active channel deposits.

I have subdivided the 2400 m study reach into three segments: A, F, and L; the downstream boundary of each segment corresponds to a lettered stream gauging station located along the mainstem channel (Figure 1). Reach boundaries also correspond to changes in the geomorphic character of mainstem channel and valley (Table 1).

Physiography

The mainstem channel of North Fork Caspar Creek is a steep (S=0.02), perennial, gravel-bed stream confined within a deeply-incised inner gorge. Throughout the study reach it is a second-order stream in which surface flow may become discontinuous during the late summer or fall. Active channel width varies between 2 m and 13 m; mean width is 4.8 m. Position of bank-side trees and occurrence of large woody debris strongly influence channel position, variability in form, and width.

The mainstem valley floor ranges from 3 m to 20 m wide along the 2400 m study reach. Valley width is influenced significantly by tributary junctions, extent of terrace

TABLE 1. GEOMORPHIC CHARACTER OF STUDY REACHES

Reach	Channel Slope	Channel Width (meters)	Valley Width (meters)	Active Channel Margins (1) (Terrace: Hillslope)	Bar plus Debris Jam Storage (m^3/m length)	Terrace Storage (m^3/m length)
A	0.016	2 to 12	5.5 to 17.5	7to3	0.9	8.4
F	0.022	1.5 to 8.5	5 to 19	7 to 3	0.4	10.1
L	0.028	1 to13	3to15	1 to1	0.7	3.5

Footnotes:
(1) ratio of length of channel bounded by terraces vs. hillslopes. For example, if reach length = 500 m, streambank length = 1000 m
if 700 m of the streambank length was directly adjacent to terraces and 300 m directly adjacent to hillslopes,
then the terrace to hillslope ratio = 7 to 3.

deposits, and the occurrence of resistant bedrock outcrops and landslide scars. Most sediment within in the active channel is stored as I) point deposits associated with jams of large woody debris and 2) along short reaches of channel that are aggrading and widening in response to adjacent recent landslides. Gravel bars in the mainstem channel are unvegetated or covered with short-lived hydrophytes.

Large woody debris jams are dynamic, short-lived features, as evidenced by a lack of mature nursed trees (trees growing up through the debris pieces) on jams and by documentation of collapse or partial collapse of many the jams from detailed mapping of large woody debris occurrence (USDA Forest Service Redwood Sciences Lab, unpublished mapping, WY 1985-1987).

Valley fill terraces define one or both channel banks along most of the channel length and become increasingly common downstream. Bank tops are typically 1 to 2 meters above the channel thalweg. Bank heights are greater than stages associated with common flows (i.e., stage = 0.6 m has a recurrence interval of 6 yr). Old-growth stumps in growth position on many valley fills confirm that some terraces were deposited hundreds of years ago, and that bank erosion and channel migration rates have subsequently been very low.

Basin hillslopes are gentle (30 to 50 percent) above a steep.inner gorge (≥ 70 percent), and ridge tops are fairly wide. Basin relief above gauging station A is 280 meters, and relief ratio for the basin is 90 m/km. Geomorphic mapping of North Fork Caspar Creek watershed above gauging station L by Spittler (CDMG, in press) reveals many ancient, deep-seated rotational slides which extend from slope base to near ridgetop. Smaller rotational block slides, shallow debris slides, and debris flows are associated with these features; and all are common throughout the inner gorge. Small debris slides and rock falls are also common along the base slopes of the inner gorge, although these features were too small for Spittler to delineate on his map. Soil wedges, debris-flow scars and deposits, and debris slides are common in unchanneled valleys throughout the watershed. Unchanneled valleys are drained by flow through the saturated soil matrix (micropores) and through naturally occurring soil pipes, 1 to 100 cm in diameter, which form a subsurface drainage net that connects sinkholes and gullies (Ziemer and Albright, 1987).

Most of North Fork Caspar Creek basin is underlain by moderately-to-intensely fractured, moderately weathered, greywacke sandstone and shale of the Coastal Belt Franciscan Assemblage (Kramer, 1976). According to Kramer (1976) and Bachman (1979), Coastal Belt Franciscan Formation in the Fort Bragg area is of late Cretaceous to earliest Oligocene or Eocene age, and consists of approximately 99 percent sandstone and shale (in a 7:3 ratio), with minor amounts of limestone, spilitic volcanics, and chert. Greywacke sandstone beds are often many hundreds of feet thick with only a few shale laminae between layers.

Caspar Creek watershed is located west of the Chamberlain fault within a shear zone where bedrock shows intense stratal disruption and boudinage (Kramer, 1976). Coastal belt sandstones are zeolite facies in the Fort Bragg area in contrast to the more-highly metamorphosed central belt sandstones that are zeolite through blue-schist facies in the Fort Bragg-Willits area (Kramer, 1976).

Merrits and Vincent (1987) have inferred that there was an increase in uplift rates on the Mendocino coast associated with the passage of the Mendocino Triple Junction based upon their documentation of the present day uplift rates in the vicinity of the triple junction which are 1) less than 1.0 mm/yr to the north of the triple junction, 2) 2.8 mm/yr to 4 mm/yr within the immediate vicinity of the triple junction, and 3) 0.3 mm/yr to the south of the triple junction. Inner gorge features common along streams of the Mendocino coast may be the product of regional tilting and high uplift rates that were associated with passage of the triple junction.

Climate

North Fork Caspar Creek watershed has a Mediterranean climate. Mean annual rainfall is approximately 1200 mm, and roughly 90 percent of rainfall occurs between October and April, typically during low-intensity cyclonic storms. Annual precipitation has varied between 840 mm and 1750 mm since monitoring began in 1962. Snowfall is very rare.

Studies by Adam (1988) in the Clear Lake area and Johnson (1977) along the California coast, suggest that 1) climate during the past 10,000 years was similar to the historical period, and 2) there appears to have been a period of greater effective precipitation between 10,000 and 70,000 years ago. Evidence of a major shift in climatic regime during Late Quaternary time, however, is lacking at these sites. Late Quaternary pollen assemblages at Clear Lake and fossil floras on the coast are typical of those associated with Mediterranean climate. Historical precipitation data and Late Holocene dendrochronologies for coastal California also document the occurrence of alternate wet and dry periods of variable extent upon which are superimposed wide, episodic annual variations in precipitation (Johnson, 1977).

Vegetation

Dense, advanced-second growth conifer forest dominated by Douglas fir (Pseudotsuga menziesii) and coast redwood (Sequoia sempervirens), western hemlock (Tsuga heteropylla), grand fir (Abies grandis), and remnant old-growth redwood and Douglas fir individuals covered the North Fork Caspar Creek basin. Understory vegetation was commonly evergreen huckleberry (Vaccinium ovatum), sword fern Polystichurn munitum), and Pacific rhododendron (Rhododendron macrophyllum).

Nearly all of the old-growth forest of North Fork Caspar Creek watershed was originally logged between 1864 and the mid-1890s, with the exception of the basin drained by tributary D-E, which was logged between 1900 and 1904 (Appendix I: Logging History of Caspar Creek Watershed). Clear-cut and selective logging of the second-growth forest of North Fork Caspar Creek watershed began during the summer of 1989.

Soils

Soils in the Fort Bragg area were resurveyed by the Soil Conservation Service in 1987. The following soil descriptions paraphrase this text (Soil Conservation Service, in press). Approximately 40 percent of the North Fork Caspar Creek watershed is mapped as Van Damme loam, which occurs at or near ridge tops, 50 percent as Irmulco-Tramway complex (loam) which occurs in mid-slope positions, and 10 percent as Dehaven-Hotel complex (gravely loam and very gravely loam) which occurs on base slopes and throughout the inner gorge. Each of these soils was formed predominately from sandstone bedrock and small amounts of mudstone. Van Damme loams are well drained and their average thickness is 1.0 to 1.5 meters. A zone of soft, highly-weathered, fractured saprolitic sandstone (Cr horizon) has formed between these soils and bedrock. Irmulco-Tramway complex soils are 0.5 to 2.0 meters deep, well drained, and underlain by soft**,** highly weathered sandstone. The Dehaven-Hotel complex soils are typically 0.5 to 1.5 meters thick, and well drained. Their infiltration capacity is very slow, and typically they overlie hard, fractured greywacke sandstones.

Hydrologic Monitoring and Previous Hydrologic Research

Long-term investigations of logging impacts on streamflow, sediment transport, sedimentation, aquatic habitat, and fisheries were initiated in 1960 and have continued through the present on North and South Fork Caspar Creek. In 1962, weirs were constructed at the downstream boundaries of these study areas to monitor streamflow, suspended-load yield, and sedimentation.

A paired watershed analysis (Rice et al., 1979) during WY 1963-1976 evaluated effects of logging roads (constructed in 1967) and timber harvest (1971-1973) on South Fork Caspar Creek and compared it to North Fork Caspar Creek, which was not logged and was considered "undisturbed". Rice (1979) concluded that logging and road building caused significant increases in suspended-load transport rates, weir pond sedimentation, and significant soil loss from South Fork Caspar Creek. Whether these impacts constituted cumulative effects is unclear. Significant increase in suspended sediment transport rates occurred in eight of the nine years after road, building and logging were begun, and would have resulted in violation of North Coast Regional Water Quality Board standards. Ziemer (1981) evaluated effects of partial cutting and road building over South Fork Caspar Creek watershed on storm flow response during WY 1963-1975 by comparing the storm flow characteristics of South and North Fork Caspar Creek. Ziemer (1981) concluded that there were no significant impacts from logging and road building on moderate and large storm peak flows. As these flows shape the channel and provide the bulk of runoff, this suggests there were no cumulative effects related to changes in streamflow.

The North Fork Caspar Creek cumulative effects study was begun in WY 1986 and has emphasized streamflow, suspended-load yield, and sedimentation monitoring to evaluate a wide range of impacts, such as timber harvest (extent of clear cutting, density of landings and skid trails), silviculture (burning of slash), and road building (road densities, percentage new and old roads). Twelve streamflow and suspended-load gaging stations were constructed throughout North Fork Caspar Creek watershed at downstream boundaries of treated and undisturbed tributaries (Figure 1). These stations have been operated continuously since their installation in WY 1983 and calibration during WY 1983-1985. Changes in LWD dam sediment storage as a result of logging are also being evaluated on the mainstem and tributaries of North Fork Caspar Creek, as part of the cumulative effects study (Ziemer, unpublished proposal). Mainstem channel LWD has been mapped annually since WY 1983 and that in tributaries since WY 1985.

Bedload transport has been monitored by USDA Redwood Sciences Lab personnel since the fall of 1988 at a bedload trap (Birkbeck Pit Sampler) constructed at gauging station A. This station should help in identifying significant changes in bedload transport rate and size distribution versus stream power, if these changes occur following logging treatments.

A network of sixty-four channel cross-sections was established over the 2400 meter study reach of mainstem North Fork Caspar Creek in the summer of 1979 by Tom Lisle, a hydrologist at the USDA Forest Service Redwood Sciences Lab. All of these cross-sections were surveyed again in the summer of 1980 and forty-eight were surveyed in the fall of 1986 by USDA Forest Service personnel. I resurveyed forty-five of these cross-sections in the summer of 1988. Channel thalweg, limits of stream bed, bar deposits, and banks can be distinguished on the cross-sections (Appendix II).

Hydrologic properties of soil series of Caspar Creek watershed, including particle size distribution and bulk density, were analyzed by Wosika (1981). He concluded that hydraulic conductivities of these soils are very high and that subsurface runoff is rapid; therefore saturation is limited in area and duration during most storm events.

Maximum peak flow at the North Fork .weir for the period of record through WY 1988 was 8.6 m^3/s on January 4, 1966, and January 16, 1974. Mean annual peak is 3.1 m^3/s. Largest peakflow during the monitoring period for the North Fork Caspar Creek sediment routing study was 5.9 m^3/s on December 21, 1982 (recurrence interval = 6.0 years). Storm runoff on North Fork Caspar Creek responds rapidly to rainfall during large storms; lag time between rainfall peak and peak runoff is typically only a few hours. Recording rain gauges are located in the headwaters and downstream end of North Fork Caspar Creek. A recording rain gauge has been operated continuously since WY 1962 at the North Fork Caspar Creek weir.

CHAPTER 2: MAINSTEM SEDIMENT STORAGE

2.1 OVERVIEW

I characterized mainstem channel and valley sediment storage by defining four landform map units and describing 1) their volume and distribution, 2) the position and elevation of individual deposits relative to active channel boundaries, 3) vegetation age, 4) depositional controls, and 5) sediment source type (particle size distribution and bulk density). I used these investigations, together with review of previously collected data and literature, to define sediment storage reservoirs: landforms of similar sediment source type and relative mobility (frequency of erosion and transport). Relative mobility of landforms was characterized through description of vegetation age, position and elevation of deposits relative to the active channel, and review of geomorphic and LWD maps made to assess sediment storage changes during WY 1985-1987.

Sediment reservoirs were used to estimate mainstem channel sediment storage changes in terms of mass by particle size class (gravel, sand, fines). Estimation of these storage changes involved measurement of reservoir lengths together with review of geomorphic maps and calculation of changes in area at channel cross-sections. Analysis of changes in sediment storage over WY 1980-1988 is presented in Chapter 3.

2.2 METHODS

Geomorphic Mapping and Volume Calculation

I mapped mainstem channel and valley deposits during the summer of 1987 utilizing LWD base maps updated in the summer of 1986 by Forest Service staff (USDA Forest Service, unpublished mapping). Geomorphic maps delineate streambed deposits (S), bar deposits (B), debris jam deposits (DJ), valley fill terrace deposits (T), active channel boundaries, and channel thalweg position. In some cases, hillslope deposits (H) define channel banks; these are also identified on geomorphic maps. I mapped landforms by compass and pace and by reference to channel margins or LWD. Positions of channel boundaries, LWD, and bedrock detailed on mainstem geomorphic maps are directly transferred from LWD base maps with minor modification for changes occurring over WY 1987 and/or slight errors in mapping of LWD or channel position.

Bar, debris jam, and terrace volumes were estimated from map area and exposed height surveyed during the summer of 1987; streambed volume was estimated from field observations of bed thickness. Heights of debris jam, bar, and terrace deposits were estimated by sighting with a hand level on a surveying rod placed at the base and top of the landform. Areas were estimated by digital planimeter traces of deposit boundaries as delineated on geomorphic maps.

Terrace Bank sedimentological Description

Visual estimates of particle size distribution (percent gravel, sand and fines), bedding, sorting, clast roundness, depositional structures, and matrix-support or clast-support were noted at bank exposures on most valley fill terraces during summer 1987 to infer depositional origin and to characterize sediment source types and mobility.

Pebble Counts

Pebble counts were carried out at randomly selected transects over streambed, bar, and debris jam map units to quantify visual distinction of differences in surface bed particle size of debris jams and streambed (used to delineate boundaries between these map units), and if differences were confirmed, to determine whether they correspond to differences in subsurface bulk particle size distribution. All particles with intermediate diameter (D_I) > 256 mm were lumped together into the 256 mm size class; particles with D_I < 4 mm were lumped together into the < 4 mm size class.

Particle Size Distribution

Church et al. (1987) served as a guide to sampling and analysis. Particle size distributions were estimated from twelve bulk subsurface samples of active channel (streambed, bar, and debris jam) deposits. Sample sizes ranged from 20 to 68 kg; most samples were 25 to 35 kg. After a surface cover layer was removed, subsurface deposits were wet-sieved in the field with 45 mm, 22.5 mm, 16 mm, and 8 min sieves (Parker and Klingeman, 1982). Sediment passing through the 8 mm sieve was subdivided into four splits, one of which was collected and dry-sieved in the lab.

From bank sedimentological descriptions, I subdivided valley fill terraces into two sediment source types: a) non-cohesive clast-supported (nT), and b) cohesive matrix-supported (cT). Particle size distribution for clast-supported valley fills was determined from sampling one clast-supported valley fill terrace in March of 1988 and from previously collected data for two other clast-supported gravel terrace deposits (USDA Forest Service, unpublished data). Particle size distribution for matrix-supported valley fills is developed from review of Benda and Dunne (1987), previously collected particle size distribution data for Caspar Creek colluvial soils (Wosika, 1981), and from review of Costa (1988).

As hillslopes define some channel banks, hillslope particle size distribution is estimated as part of the process of describing sediment source types (particle size distribution and mass to volume ratio). Hillslope particle size distribution is developed from review of previously collected data (Wosika, 1981).

Bulk Density

I used bulk density data collected in 1980 from the gravel delta above the North Fork Weir to characterize streambed, bar, and debris jam bulk density. Three samples each were collected at nine channel cross-sections located at irregular intervals over the gravel delta, which typically forms over an area 300 feet to 390 feet upstream of the North Fork Weir. Gravel delta bulk density sample size varied from 0.19 kg to 0.83 kg. Gravel delta bulk density (1.83 tonnes per m^3) was developed from weighted distribution of these samples.

Bulk density estimates for hillslope deposits are developed from data in Wosika (1981). I used Wosika's data for samples located in inner gorge settings within 100 meters of the mainstem channels of North and South Fork Caspar Creek.

Bulk densities of cohesive valley fills (matrix-supported silty-clays and gravels) and non-cohesive valley fills (clast-supported gravels) were estimated from bank sedimentological descriptions, review of Costa (1988) and Wosika (1981), and literature describing sediment porosity versus texture (Dunne and Leopold, 1978).

Depositional Controls

Field observation of hydraulic controls during mapping and from review of geomorphic maps were used to evaluate depositional controls of bars; bank sedimentology was used to suggest valley fill depositional processes, and WY 1985-1987 LWD mapping (USDA Forest Service, unpublished mapping) was analyzed to evaluate when jams formed and how sediment storage changed.

2.3 MAP UNIT DESCRIPTIONS

Streambed

I define the streambed (S) map unit as all active channel sediment not stored in bars or debris jams. Streambed extends beneath bars and debris jam sediment wedges (Figure 2). Streambed is nearly flat to concave in cross-section; streambed relief is less than 0.1 m. Surface layer particles are commonly coarse pebble to cobble size (D_{84} = 92 mm); and very coarse relative to bar and debris jam map units (Table 2). Pebble counts suggest the surface layer of the streambed is poorly sorted relative to bar and debris jam deposits.

Comparison of streambed surface and subsurface layers suggests that: 1) the bed surface is well armored; and therefore 2) the streambed has the capability to adjust to an increase in bedload transport rate simply by a textural response - fining of the surface bed layer - without substantial modification of bed topography or increase in sediment storage (Dietrich, 1989).

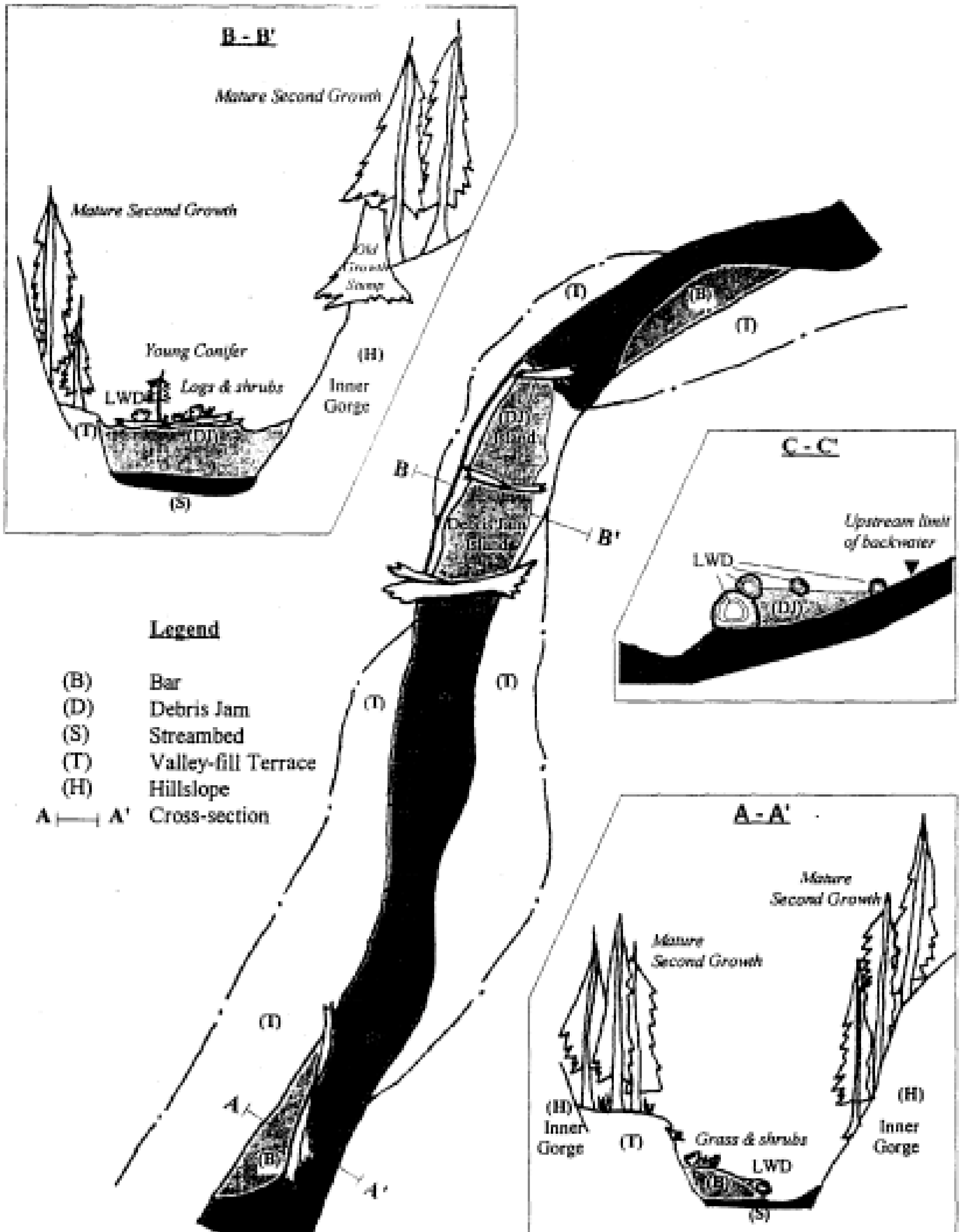

FIGURE 2. Definition sketch of geomorphic mapping units: Map and section views of sediment storage reservoirs. Limits of streambed, bars, and debris jams are most easily distinguished by surface layer particle size, shape of the deposits, and topographic relief. Terrace deposits are distinguished by vegetation (mature conifers) and typical height (h > 0.6 m) above the channel thalweg.

TABLE 2. PARTICLE SIZE DISTRIBUTIONS FOR ACTIVE CHANNEL MAP UNITS

Streambed Particle Size Distribution			
Surface Bed (pebble counts)	D_{84} = 92 mm	D_{50} = 36 mm	D_{16} = 9 mm
5 sites, N=507			
Subsurface (bulk samples)	% gravel	% sand	% fines
5 sites, composite mass = 165.97 kg	81.36	18.43	0.21
	D_{84} ≥ 2 45 mm	D_{50} = 11 mm	D_{16} = 1 mm
Bar Particle Size Distribution			
Surface Bed (pebble counts)	D_{84} = 33 mm	D_{50}= 13 mm	D_{16} = 5 mm
4 sites, N=402			
Subsurface (bulk samples)	% gravel	% sand	°% fines
4 sites, composite mass = 153.88 kg	81.74	18.01	0.25
	D_{84} ≥ 45 mm	D_{50} = 10 mm	D_{16} = 1 mm
Debris Jam Particle Size Distribution			
Surface Bed (pebble counts)	D_{84} = 24 mm	D_{50} = 1 l mm	D_{16} = 6 mm
3 sites. N=315			
Subsurface (bulk samples)	% gravel	% sand	% fines
3 sites. composite mass = 104.48 kg	74.63	25.32	0.05
	D_{84} = 21 mm	D_{50} = 7 mm	D_{16} = 1 mm

I estimate total streambed volume as ≤ 3500 m³ based on mean WY 1980 active channel width measured at sixty-five channel cross-sections together with field observations of alluvial thickness measured during the summer of 1987 (3500 m³ volume ≈ 0.3 m observed mean thickness x 4.85 m active channel width x 2400 m study reach length).

I used bulk subsurface samples to estimate particle size distribution for all active channel deposits - streambed, bar, and debris jam (Table 2). Streambed and bar subsurface samples contain nearly identical percentages of sand, gravel, and fines: they contain approximately 80 percent gravel and 20 percent sand.

I used the bulk density of the North Fork delta samples to characterize bulk density of all active channel deposits (Table 3). I believe the gravel delta depositional setting is most similar to the backwater zone of a debris jam, although the gravel delta deposits have a much larger percentage sand and fines (39 percent) than streambed (19 percent), bars (18 percent), and debris jams (25 percent). This suggests bulk density of streambed, bar, and debris jam deposits may be somewhat less than gravel delta bulk density as gravel delta deposits are poorly sorted in comparison to active channel deposits (e.g. the matrix between gravel clasts contains more sand).

TABLE 3. BULK DENSITY FOR ACTIVE CHANNEL MAP UNITS DEVELOPED FROM SAMPLING THE NORTH FORK GRAVEL DELTA

Gravel Delta Bulk Density (1980)*

cross-section reach (feet upstream of weir)	fractional length (a)	bulk density (tonnes/m³)	fractional value (b)
300-315	0.17	1.80	0.30
315-323	0.09	1.71	0.15
323-333	0.11	1.58	0.18
333-343	0.11	1.80	0.20
343-355	0.13	2.03	0.27
355-360	0.06	1.99	0.11
360-370	0.11	2.00	0.22
370-380	0.11	1.90	0.21
380-390	0.11	1.72	0.19
sum=	1.00	Weighted Average bulk density (tonnes/m3) =	**1.83**

Notes: (a) fractional length: the gravel delta covers approximately 90 feet along the centerline of the channel over the weir pond. If the distance between two pond cross-sections is 15 feet (i.e., reach 300-315), then the fractional length is 15 ft / 90 ft = 0.17.

(b) fractional value = (weight proportion) x (bulk density), for each pond cross-section reach.

Particle Size Distribution Comparison: Delta, Streambed, Bar, and Debris Jam.

	Delta (1980)*	Delta (1987)**	
% Gravel	61.2	63.30	
% Sand and Fines	38.8	36.70	
	Streambed	Bar	Debris Jam
% Gravel	81.4	81.7	74.6
% Sand and Fines	18.6	18.3	25.4

Footnotes:

* Summer 1980 sampling (USDA Forest Service, unpublished data)
** Summer 1987 sampling (USDA Forest Service, unpublished data)

<u>Debris Jam</u>

Debris jams are defined by LWD (diameter ≥ 0.1 m) resting on the streambed over most to all of the active channel width; long axes of LWD are usually approximately normal to streambanks. Jams create backwaters causing deposition of bedload at high flows. As a result, the channel develops a stepped longitudinal profile that extends across most to all of its width (Figures 2 and 3). Nursed trees (conifer sprouts from LWD trunks defining the jam) are rare and where present appear to be very young (diameter ≤ 0.1 m); water-loving grasses and shrubs are common on higher surfaces of sediment stored within the backwater area of jams.

I defined the upstream limit of debris jams as that point where bed elevation approximates the elevation of the upper edge of LWD control (the highest stable trunk within the jam), and from visual distinction of an abrupt increase in surface bed particle size where debris jams abut streambed deposits. Pebble counts support the argument that debris jam surface bed particles are much finer and better sorted than streambed deposits (Table 2).

Total volume of debris jam deposits is 710 m^3 (Table 4). Cumulative volume versus long profile position is presented in Figure 4, which illustrates that: 1) cumulative debris jam storage volume increases in a uniform fashion; and 2) there is a marked contrast in

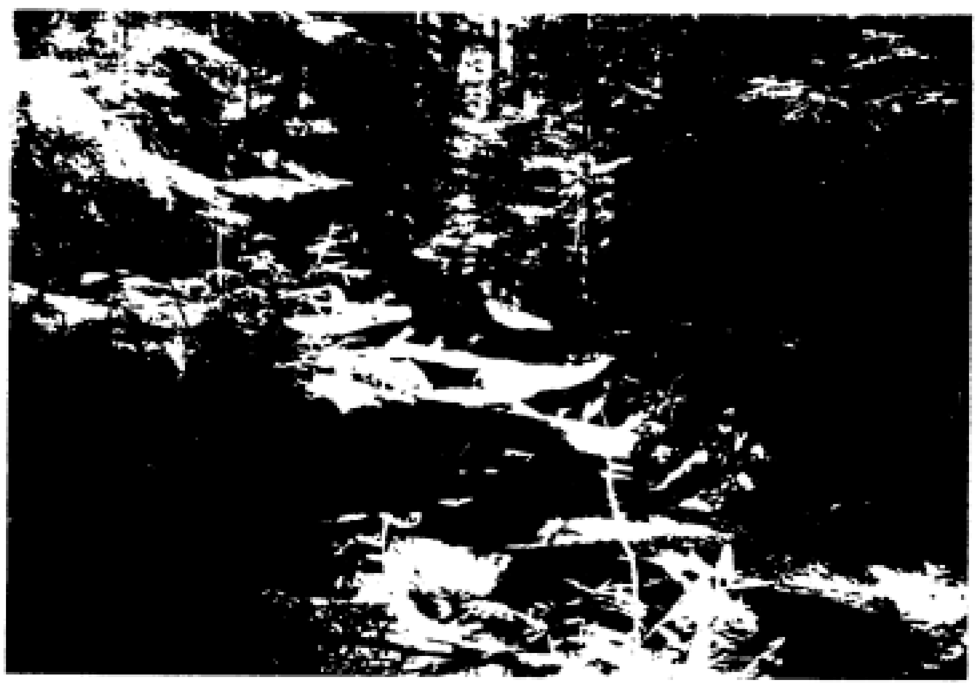

FIGURE 3. Large woody debris jam (O5) located in map reach A28-A35. Note: step in stream-bed profile, plunge pool below the jam, and well-sorted fine gravel deposited in the backwater of the jam. Debris jam (O5) is also illustrated in map view in Figure 8.

TABLE 4. SEDIMENT STORAGE DISTRIBUTION

Sediment Routing Reach	Channel Map Reach	Channel Map Reach Length (m)	Bar (m³)	Debris Jam (m³)	Valley Fill Terrace (m³)
A	A1-A5	105	50	0	750
	A6-A9	100	15	55	500
	A10-A12	100	30	35	700
	A 13-A 15	80	15	0	700
	A 16-A 19	150	30	70	1700
	A 19-A22	125	190	0	1450
	A23-A27	140	145	0	1000
	A28-A35	150	35	60	1450
	A35-A39	145	105	120	1000
totals:		**1095**	**615**	**340**	**9250**
F	A39-A46	165	40	20	650
	A45-A51	155	50	85	650
	A52-A55	120	20	5	2150
	A57-A64	185	15	55	2150
	A64-A70	130	10	30	2050
totals:		**755**	**135**	**195**	**7650**
L	R1-R10	170	55	35	1250
	R10-R19	155	25	55	500
	R19-R27	160	140	65	150
	R27-11.34	115	5	20	200
totals:		**600**	**225**	**175**	**2100**
	Study Reach Totals:	**2450**	**975**	**710**	**19000**

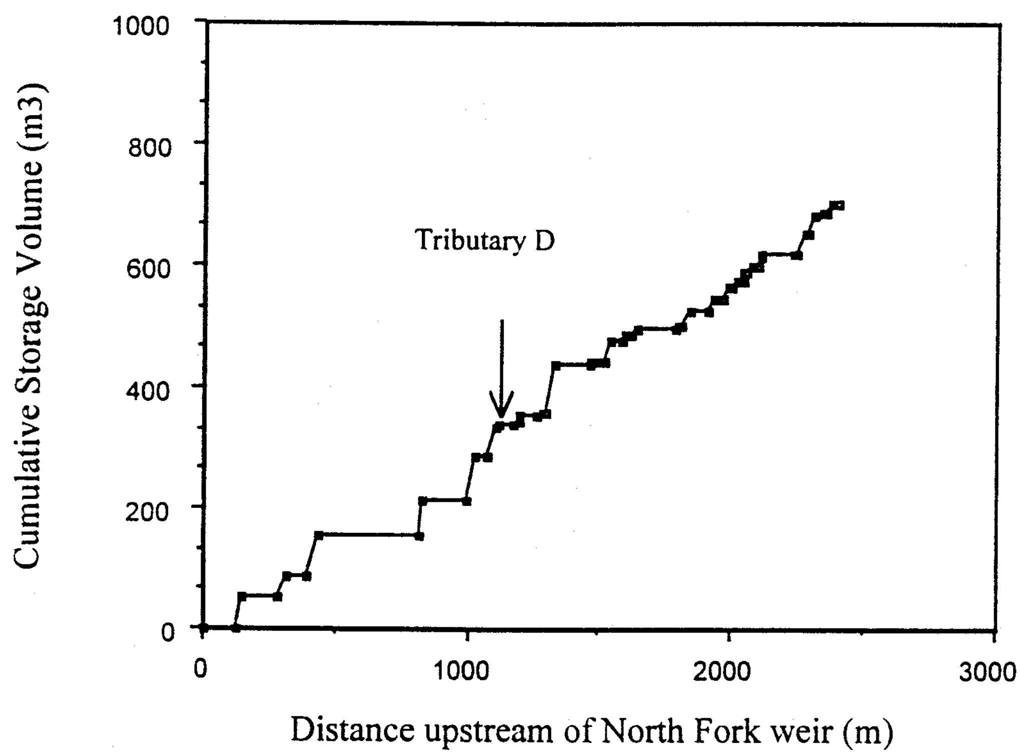

FIGURE 4. Debris jam sediment storage

spatial distribution and mean storage capacity of debris jams above and below the confluence of tributary D (Table 5). Below D, the influence of LWD jams on channel form and process is concentrated at large discrete accumulations (Table 5). Lack of small jams below D suggests that these jams are easily mobilized during common storm flows (recurrence interval ≤ 1 year). Large jams (storage volume > 25 m^3) below D form at 1) prominent bends (Figure 5 and Figure 6); 2) just upstream of narrow channel segments (Figure 7) where floated debris is obstructed; 3) adjacent to recent debris-slide scars (Figure 8); and 4) adjacent to collapsed logging structures composed of old-growth-size LWD elements (Figure 5).

Above tributary D, there appear to be two to three size classes of LWD jams (small, medium, and large jams). Narrow reaches are more common above D (Table 6); this may 1) limit the occurrence of large jams formed by accumulation of floated debris, and 2) allow smaller pieces of LWD to wedge between streambanks and remain stable during flows capable of bedload transport.

Particle size distribution for debris jams is presented in Table 2: debris jams contain approximately 75 percent gravel and 25 percent sand; the percentage of sand is somewhat greater and fines are slightly lower than for streambed and bar samples.

TABLE 5. DEBRIS JAM SIZE CLASSES AND STORAGE VOLUMES

Reach	Length (m)	Number of Debris Jams	Mean Volume (m^3)	# of Large (>25m^3)	# of Medium (6 to 25 m^3)	# of Small (<6 m^3)
Below D	1095	6	56.0	6	0	0
Above D	1355	29	12.7	5	11	13

Notes:

Large Jams, below Tributary D (mean storage)= 56.0 m3

Large Jams, Above Tributary D (mean storage)= 38.9 m3

Medium Jams, Above Tributary D (mean storage)= 12.5 m3

Small Jams, Above Tributary D (mean storage)= 2.8 m3

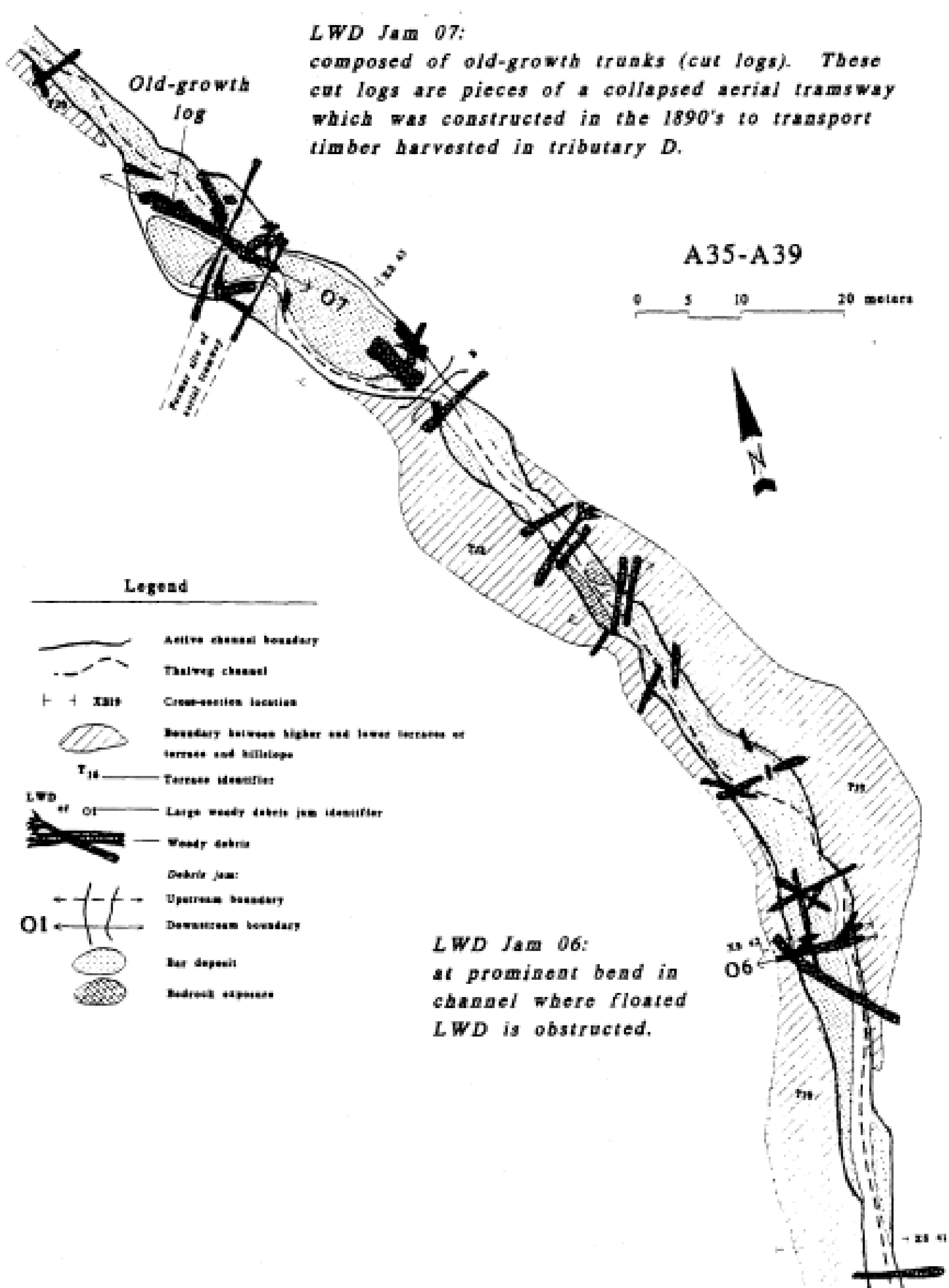

FIGURE 5. Large woody debris jams: (06) formed at a prominent channel bend and (07) composed of old-growth logs.

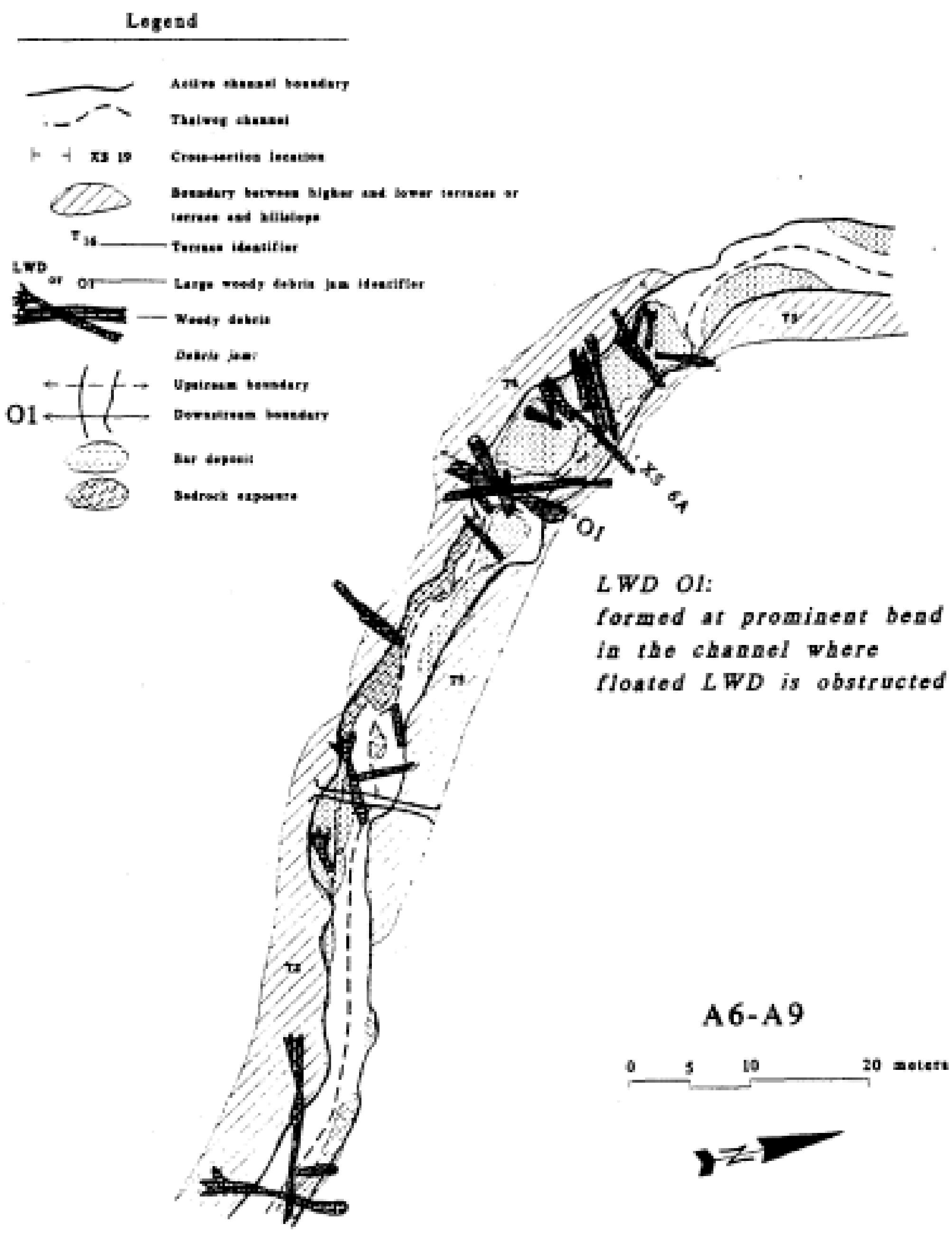

FIGURE 6. Large woody debris jam (01) formed at a prominent channel bend.

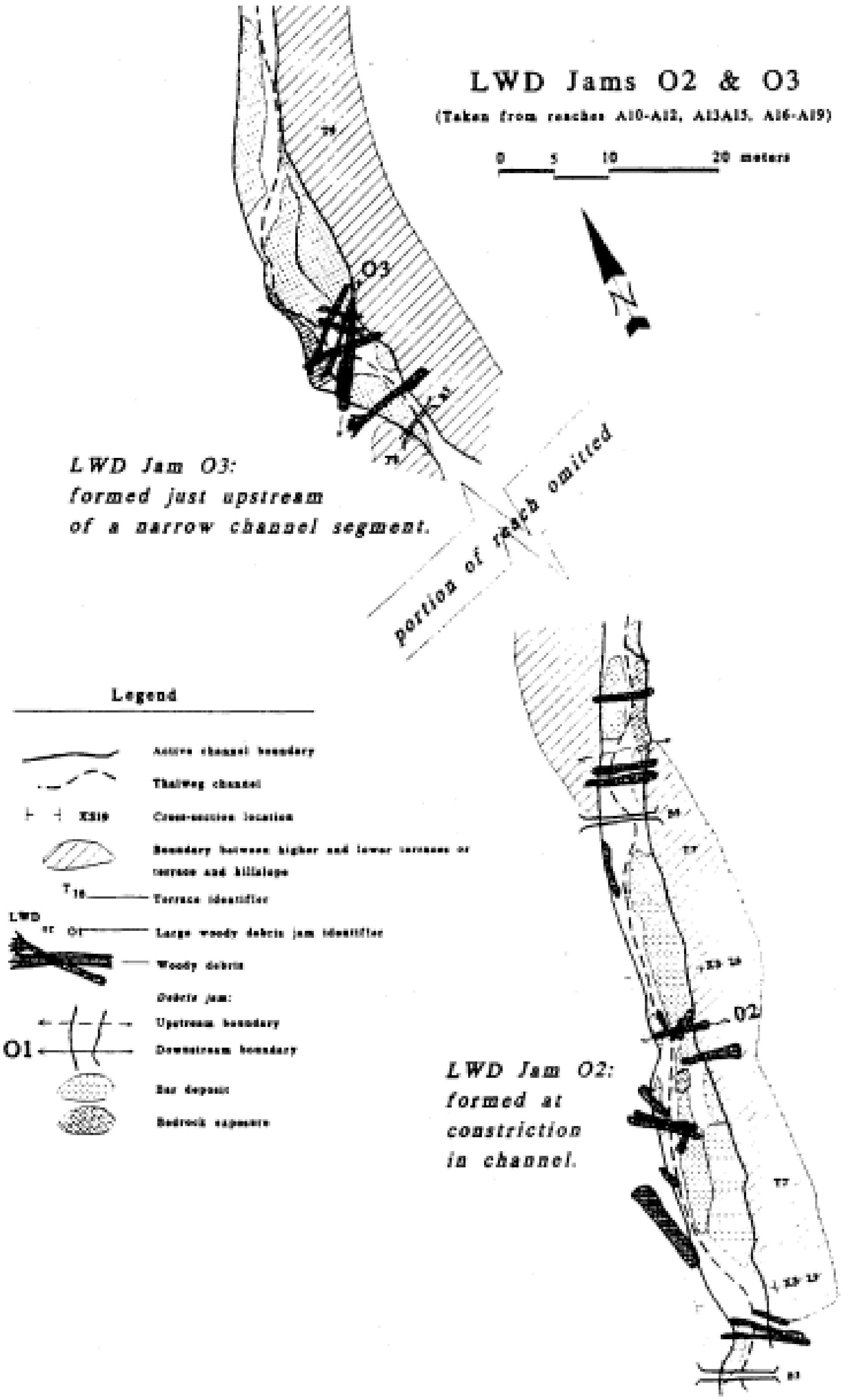

FIGURE 7. Large debris jams (O2 and O3) formed at channel constrictions.

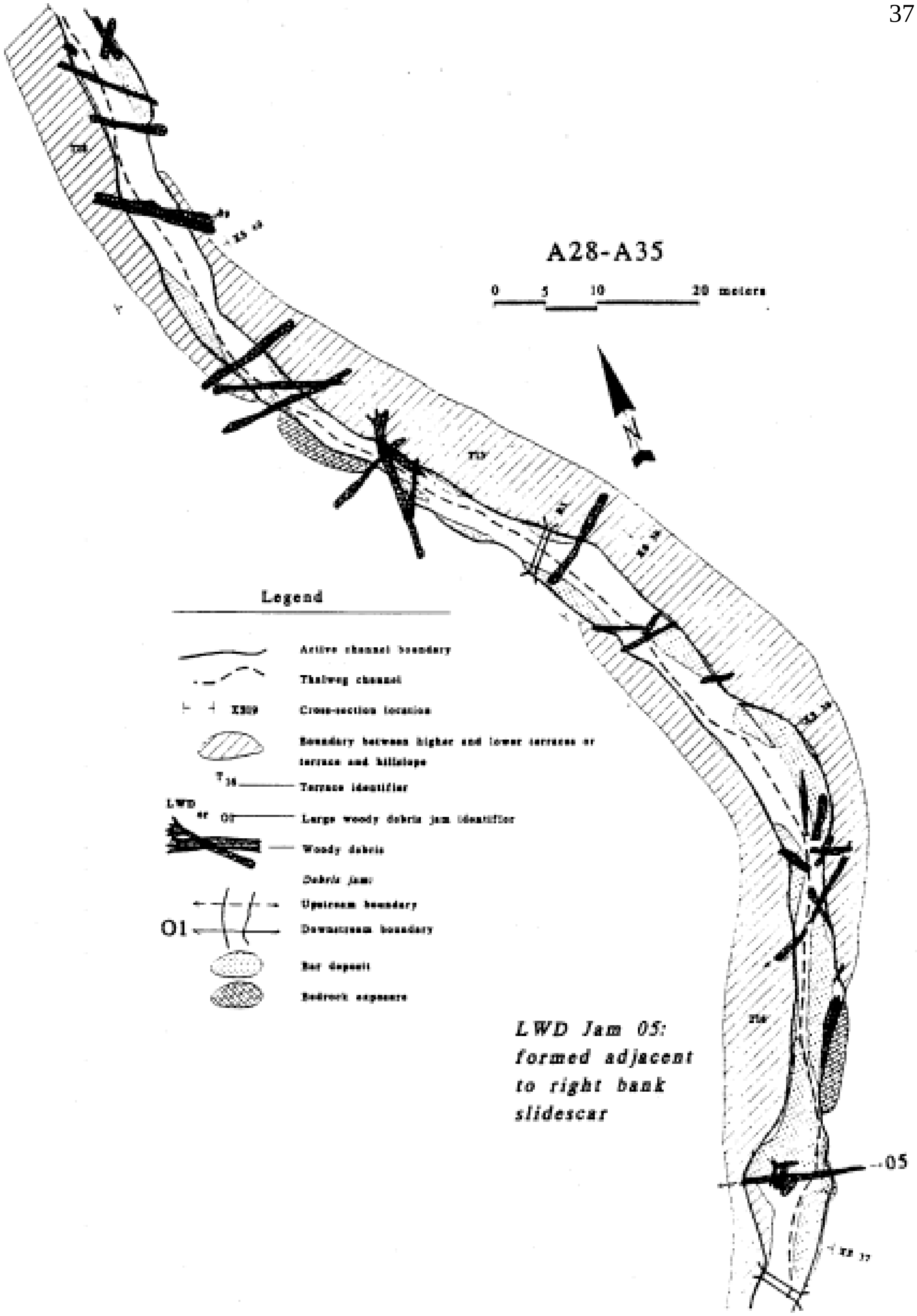

FIGURE 8. Large debris jam (05) formed adjacent to right-bank slidescar.

TABLE 6. ACTIVE CHANNEL WIDTH ABOVE AND BELOW TRIBUTARY D

Cross-sections Below D

Cross-Section	Width (m)
25	4.8
26	4.4
27	3.7
28	6.7
29	3.0
30	1.9
31	3.3
32	6.1
33	3.3
34	9.6
35	5.9
36	3.3
37	5.6
38	7.0
39	6.7
40	5.2
41	3.3
42	6.7
43	9.6
Mean width =	**5.3**

(9 of 19 cross-sections, w < 5 m)

Cross-sections Above D

Cross-Section	Width (m)
44	5.0
45	2.2
47	4.1
48	3.3
49	3.7
50	3.3
51	5.6
53	4.1
54	3.3
56	5.6
57	2.4
58	3.3
59	4.4
60	3.3
62	3.0
63	6.5
64	4.8
65	6.7
66	4.1
67	2.8
68	3.5
69	4.1
70	4.4
71	1.5
72	6.3
73	6.3
74	6.7
76	8.5
77	9.6
78	3.7
79	3.7
80	2.6
Mean width =	**4.4**

(22 of 32 cross-sections, w < 5 m)

The lack of long-lived vegetation on LWD jams and on backwater sediment accumulations (the largest nursed trees are < 0.05 m in diameter and 0.3 m in height) suggests that sediment stored by LWD jams is frequently mobilized and/or jams are recently formed or modified. These assertions are supported by analysis of the time of formation and recent sediment storage changes (WY 1985-1987) for large jams (e.g., sediment storage ≥ 25 m^3) in Table 7 which suggest: 1) five or more of eleven large jams formed sometime during WY 1979-1985; and 2) two large jams, O17 and O33, partially collapsed sometime during WY 1985-1987; and 3) one large jam, O2, formed sometime during WY 1985-1987. Peak flow during WY 1985-1987 had a recurrence interval of only 2.5 years.

I define bars as topographic benches 0.1 m to 0.6 m above the adjacent streambed (Figure 2). Most terrace surfaces are 1.0 m or more above the streambed; all benches less than 0.1 m high were lumped together with streambed deposits. Based upon my definition, floodplains, with typical height of 0.4 m to 0.5 m, are lumped into the bar map unit. I lumped floodplains and bars together into the bar map unit because 1) North Fork Caspar Creek is entrenched (entrenchment < 1.4) and it has a low width-to-depth ratio (width/depth ≤ 12) (Rosgen, 1994) - therefore its floodplains are narrow, discontinuous, and limited in areal extent and volume; and 2) floodplains and bars in

TABLE 7. LARGE DEBRIS JAMS (≥ 25 M3): TIME OF FORMATION AND RECENT STORAGE CHANGES

Reach Length (meters)	Geomorphic Map I.D.	Location	Debris Jam Formed (water year)	1987 Storage (m^3)	1985-1978 Change in Storage (l)	Evidence from 1985-1986 LWD Maps and 1987 Geomorphic Maps*
A 1120	O1	80 m upstream of xs 9	1980	53	0-10 m3 increase	jam formed in 1980, as noted in 1980 cross-section survey; long bars and some LWD pieces first shown on 1986 map
	O2	25 m upstream of xs 25	1984 or 1985	34	20-30 m3 increase	LWD jam but no bars on 1985 map; cross-section 26 end-pins missing in 1986; step and small bar shown on 1986 map
	O3	15 m downstream of xs 28	before 1979 (2)	71	0-10 m3 increase	few LWD pieces and no bars on 1985 map; long bar on 1986 map
	O5	8 m upstream of xs 37	before 1979 (2)	58	0-10 m3 increase	most bars and LWD on 1985 map; no significant changes 1986-87
	O6	2 m downstream of xs 42	between 1979 and 1985 (3)	73	0-10 m3 decrease	stepping noted 1985; step breached 1986, but most stored sediment remained in jam
	O7	15 m upstream of xs 43	before 1979 (2)	47	No significant change	No changes evident 1985-87

Reach Length (meters)	Geomorphic Map I.D.	Location	Debris Jam Formed (water year)	1987 Storage (m3)	1985-87 Change in Storage (l)	Evidence from 1985-1986 LWD Maps and 1987 Geomorphic Maps*
F 695	O14	16 m upstream of xs 50	between 1979 and 1985 (3)	77	no significant change	no changes evident 1985-87
	O17	17 m downstream of xs 56	before 1979 (2)	32	0-20 m3 decrease	step collapsed 1986, but most stored sediment remained in jam
	O24	26 m upstream of xs 60	before 1979 (2)	29	no significant change	no changes evident 1985-87

TABLE 7 (cont.). LARGE DEBRIS JAMS (≥ 25 M3): ANALYSIS OF TIME OF FORMATION AND RECENT STORAGE CHANGES

Reach Length (meters)	Geomorphic Map I.D.	Location	Debris Jam Formed (water year)	1987 Storage (m^3)	1985-1987 Change in Storage (l)	Evidence from 1985-1986 LWD Maps and 1987 Geomorphic Maps*
L 590	O33	16 m downstream of xs 74	before 1979 (2)	33	0-20 m3 decrease	no changes evident on maps; 1986-88 scour at cross-section 74 suggests a decrease in storage
	O35	17 m downstream of xs 76	between 1979 and 1985 (3)	27	no significant change	no changes evident 1985-87

Total storage as Large Jams (volume ≥ 25 m3):

Footnotes:
(1) Analysis of Changes shown on 1985 and 1986 Large Woody Debris (LWD) Maps (USFS, unpublished mapping) and inferred from Geomorphic Maps prepared in 1987.
(2) based upon review of field notes evaluating LWD controls on deposition at cross-sections when they were established in July of 1979.
(3) No LWD control in 1979; LWD jam shown on 1985 maps.

North Fork Caspar Creek have similar vegetation cover, height, and position, and therefore, I believe, similar frequency of mobilization and/or deposition.

Bars and floodplains form at channel bends and tributary junctions. Bars also form: 1) in the lee of LWD and of boulders where tractive stress is abruptly reduced; 2) adjacent to recent and recovered slide scars; and 3) at sites of remnant debris jams where sediment is stored in the lee of the remaining LWD trunks. Bar surface particles are commonly fine to medium pebbles: D84 = 29 mm (Table 2). In summer of 1987, bars were either unvegetated or covered by grasses, shrubs, other phreatophytes, and occasionally a few very young conifers (trunk diameter ≤ 0.05 m); floodplains were typically covered by grasses or shrubs.

Bar (map unit) storage is 975 m3 (Table 4), the vast majority (64 percent) is associated with local channel aggradation and widening adjacent to: 1) recent landslides (Table 4 and Figures 9-11); 2) tributary junction fans; and 3) former debris jams and recovered slide scars. These areas of aggradation and widening are represented by steep increases in the slope of the bar cumulative storage volume curve (Figure 9) between approximately 500 m to 1000 m, and 2100 m to 2300 m upstream of the North Fork weir. Table 8 summarizes depositional controls for bars. Bars and floodplains formed

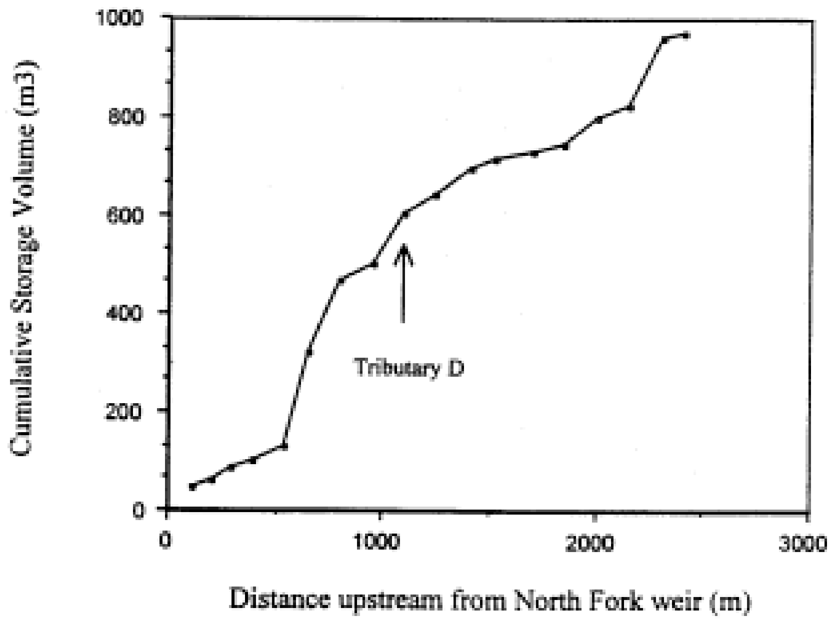

FIGURE 9. Bar sediment storage distribution

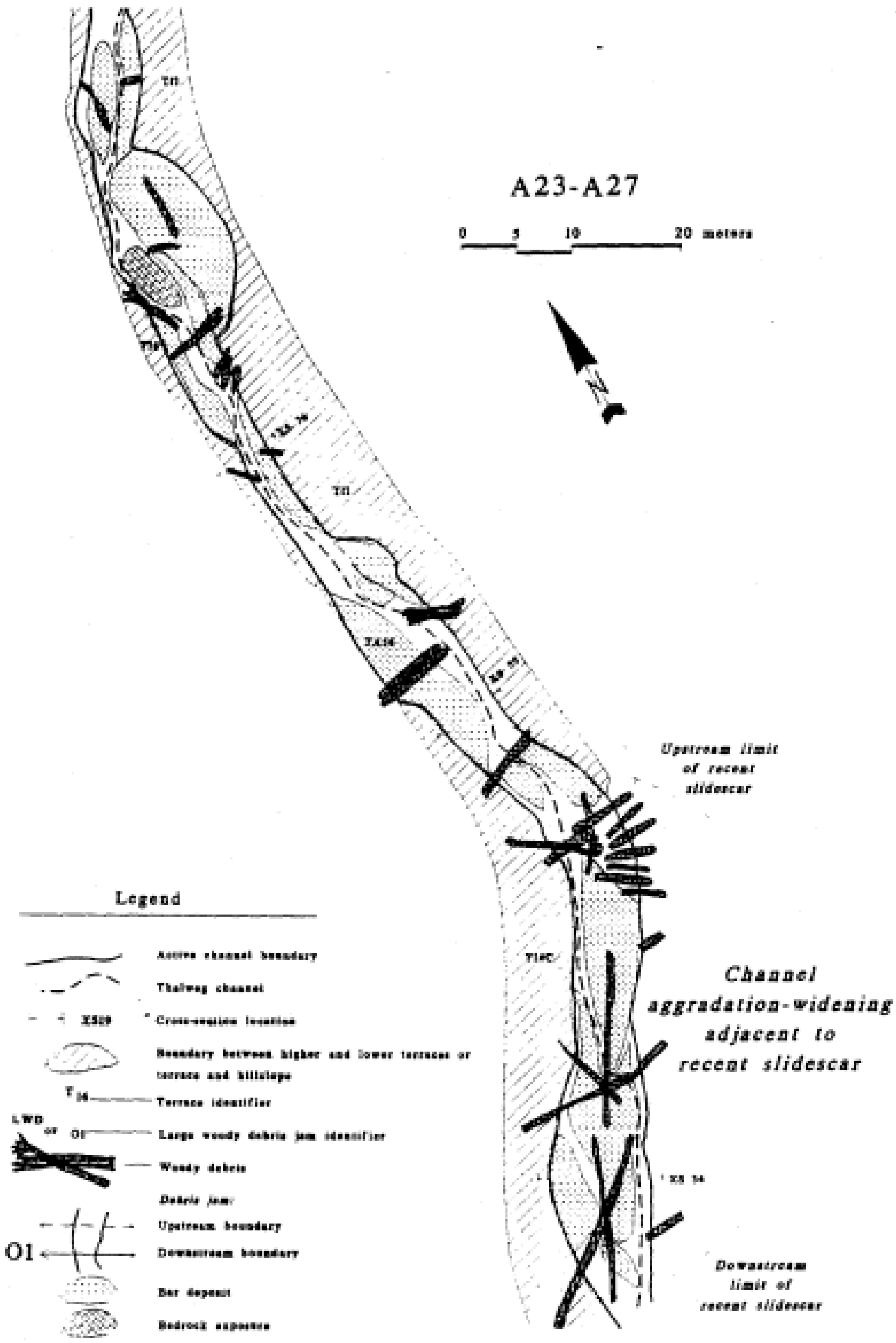

FIGURE 10. Channel aggradation and widing adjacent to a recent landslide scar in map reach A23-A27.

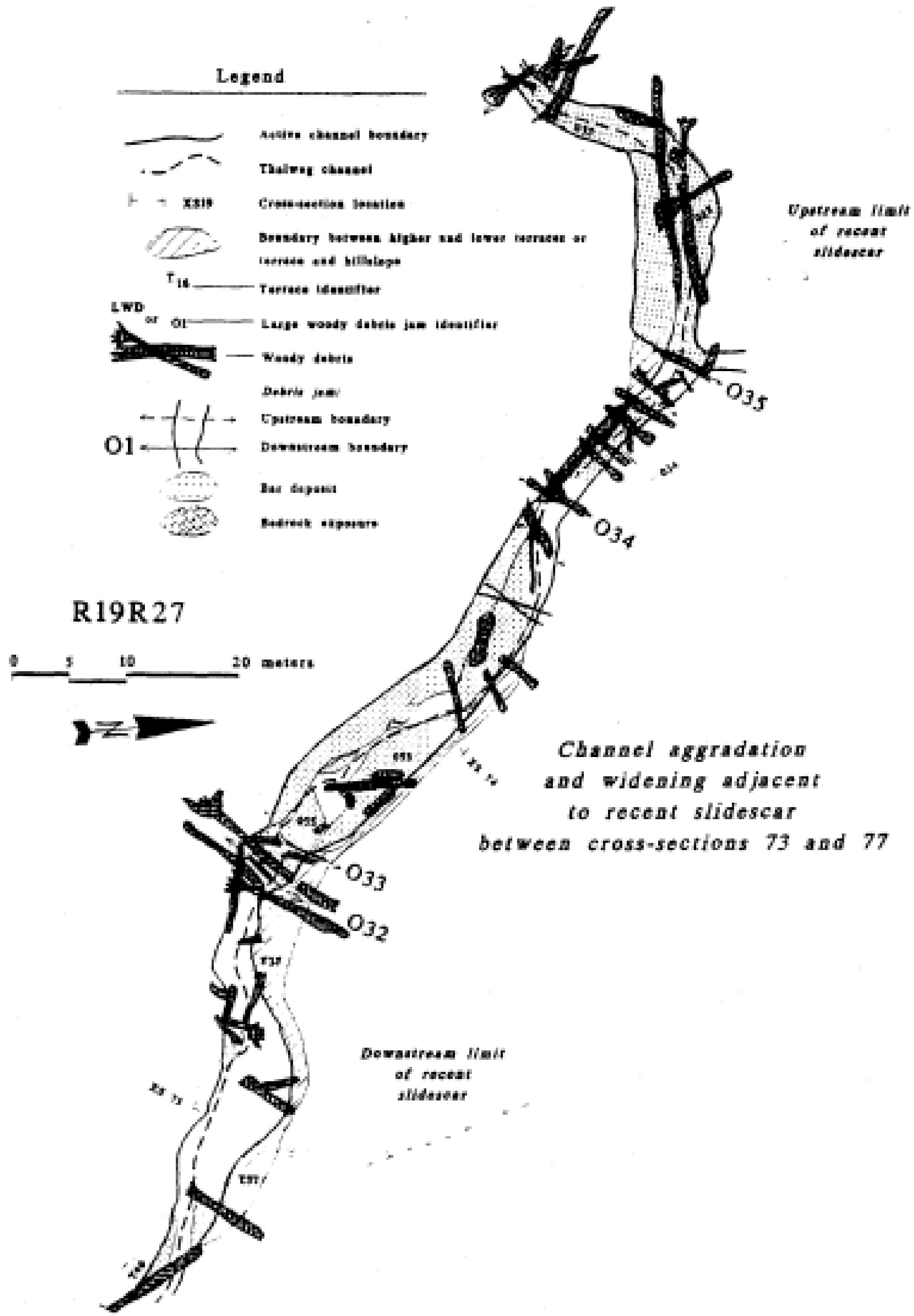

FIGURE 11. Channel aggradation and widening adjacent to a recent landslide scar in map reach R19-R27.

TABLE 8. DEPOSITIONAL CONTROLS FOR BARS

Association or Control	Volume (m^3)	% of Total
aggradation and widening adjacent to recent landslides	355	36
aggradation and widening at former debris jams. and tributary fans	270	28
alluvial features	205	21
large woody debris not forming debris jams	145	15
TOTAL:	975	100

at channel bends and tributary junctions (alluvial controls) constitute 205 m^3 or approximately 21 percent of total bar (map unit) storage. Approximately 145 m^3 of bar storage, 15 percent of the total, is deposited in the lee of LAD not forming debris jams.

The absence of long-lived vegetation on bar and floodplain surfaces suggests that most were recently mobilized or deposited. Flows approximating a 0.6 m stage have a recurrence interval of 6 years at gauging station A; this suggests all bar and floodplain surfaces may be scoured during flows with recurrence intervals of less than 6 years. Subsurface particle size distribution for bar (map unit) deposits, roughly 80 percent gravel and 20 percent sand, is approximately the same as that of the streambed (Table 2); bulk density estimate is discussed above and presented in Table 3.

Valley Fill Terrace

I define valley fill terraces as deposits with mean bank height > 0.60 m above the adjacent channel bed. Most terrace banks are 1 m to 2 m above the channel bed and usually covered by mature second-growth conifers; many also have old-growth stumps in growth position. Terraces are usually 50 m-or-more in length, and a few -hundred to a few-thousand cubic meters in volume.

Valley fills store approximately 19000 m^3 of sediment. Valley till sediment storage varies considerably over the three reaches (Figure 12 and Table 4). It is much greater

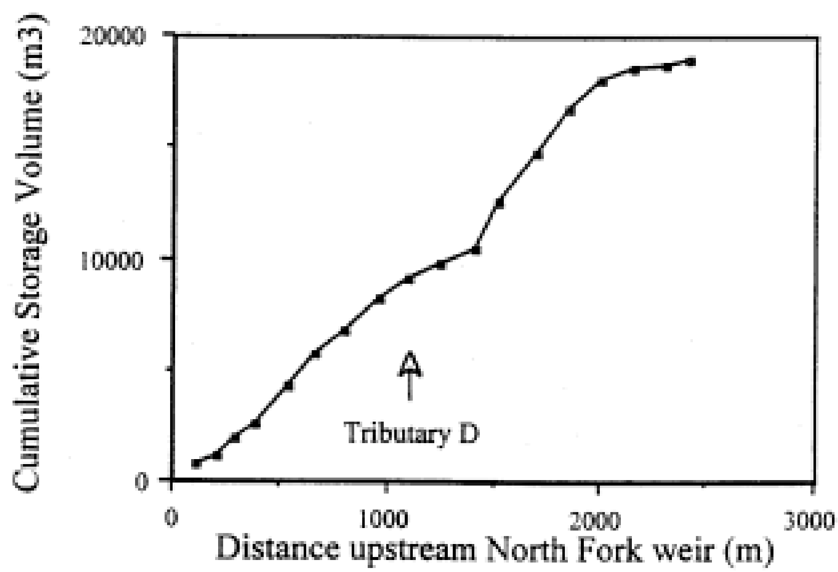

FIGURE 12. Valley fill sediment storage distribution

in reaches A (8.3 m^3/m) and F (11.0 m^3/m) than in L (3.9 m^3/m). Much lower volume per meter length in L may be related to steeper channel slope and narrower valley width in reach L (Table 1) which could cause a greater portion of sediment delivered to the reach to be transported through.

Three types of valley fill deposits (non-cohesive clast-supported gravels, cohesive clast-supported gravels, and cohesive silty clays) were defined from sedimentological descriptions of bank exposures, which are summarized in Table 9. Almost all terrace banks below tributary D are non-cohesive clast-supported gravels (Table 9). Poor sorting, weak horizontal stratification, and weak imbrication suggest that these valley fills were deposited after being transported short distances along the channel during floods (Costa, 1988). A fine cap of silt and sand present on many deposits also suggests overbank deposition. The presence of many slidescars on inner gorge slopes throughout reach A suggests that debris slides and debris flows originating on inner gorge slopes were primary sources of sediment that were reworked during fluvial transport over short distances.

Above tributary D, terrace sedimentology is more varied. Based upon bank sedimentological descriptions, I delineated three categories of deposits above tributary D: a) clast-supported gravel (as described above), b) cohesive matrix-

TABLE 9. VALLEY FILL BANK SEDIMENTOLOGICAL DESCRIPTIONS

Terrace Type	Description
Non-Cohesive Clast-Supported Gravels	Fine sand and silt overlying clast-supported, subangular to subrounded gravels, with lesser amounts of sand. Usually poorly sorted, normally graded-to-ungraded, weak horizontal stratification to massive, and imbrication is weak-to-strong.
Cohesive Matrix-Supported Gravels	As above except; silt and clay matrix, absence of stratification, very poor sorting, and angular to subangular clasts. Based upon sedimentology, depositon by debris flows is inferred.
Cohesive Silty Clays	Dominated volumetrically by blue-grey (gleyed) silty-clay containing lesser amounts of (usually) unstratified, angular to subangular fine to medium gravel clasts. Approximate proportion of gravels varies considerably (<5 to 30%) even within a particular deposit.

supported gravel, and c) cohesive silty clay deposits (with lesser amounts of gravel). Clast-supported terrace deposits above D are similar to those below it, suggesting fluvial deposition. Cohesive matrix-supported gravel deposits (Table 9) are also present above tributary D and are distinguished from clast-supported deposits by an increase in the proportion of matrix and by finer particle size (silt and clay). Absence of stratification, very poor sorting, clast angularity (angular to subangular), and clay-rich matrix support suggest deposition by debris flows. Cohesive silty clay deposits are most common between tributaries G and H. These deposits are dominated volumetrically by a blue-gray (gleyed), silty clay containing lesser amounts of gravel clasts (Table 9).

Hyper-concentrated flows are transitional between water floods and debris flows in terms of sediment concentration and flow and fluid properties (Costa, 1988). Deposits of hyper-concentrated flows are poorly documented. They are commonly described as massive to crudely stratified with thin gravel lenses, and normal to reverse grading. This description matches some silty clay bank exposures between G and H; however, sediment characteristics for banks described at these and other locations are much more similar to those attributed to debris flows by Costa (1988). Hyper-concentrated flows develop when deep-seated slides and flows of fine grained material enter channels and are fluidized (Dunne and Leopold, 1978). Geomorphic mapping of North Fork Caspar Creek watershed above station L by Spittler (CDMG, in press) reveals many ancient, deep-seated rotational slides which extend from slope base to near ridgetop. During my field work, I observed that many of these features were predominantly composed of deeply weathered and/or intensively sheared sandstone and shale bedrock.

Particle size distribution for clast-supported valley fills and cohesive matrix-supported valley fills are presented in Table 10. Particle size distribution of clast-supported valley fill is estimated as approximately 80 percent gravel, 17 percent sand, and 3 percent silt and clay. Particle size distribution of matrix-supported valley fill is estimated as 27% gravel, 34% sand, and 39 percent silt and clay.

Based upon review of Benda and Dunne (1987), and bank sedimentological features suggesting that most North Fork Caspar Creek cohesive valley fills are debris flow deposits, I assumed that particle size distribution estimates for hillslope deposits apply to cohesive valley fills (matrix-supported gravels and silty clay deposits). Benda and Dunne analyzed particle size distribution for colluvial hollows, debris flows, and first-order and second-order channel deposits in a 52 km^2 watershed in the Oregon Coast

TABLE 10. PARTICLE SIZE DISTRIBUTION AND BULK DENSITY FOR NON-COHESIVE AND COHESIVE TERRACE DEPOSITS

Terrace Type	Bulk Density tonnes/m3)	% Gravel	% Sand	% Silt & Clay
Non-cohesive (a)	1.83	80.4	16.5	3.1
Cohesive (b)	1.5	27.0	34.0	39.0

Notes:

(a) bulk density assumed equal to gravel delta deposits. Particle size distribution developed from a weighted distribution of three samples with total weight = 13.5 kg.

(b) bulk density suggested from observation of bank exposures and review of literature describing relationships between texture and porosity in natural deposits
(Dunne and Lepold, 1978). Particle size distribution assumed equal to that for H reservoir.

Range. Their results suggest valley fills and channel deposits in first and second order streams with slope < 10 percent have particle size distributions similar to colluvial hollows and debris flows.

Bulk density values for cohesive and non-cohesive valley fills are presented in Table 10. From bank sedimentology descriptions, I assume that non-cohesive valley fills are fluvial deposits, and therefore, I can apply the active channel bulk density estimate to them. Based upon field observations at exposed banks (porosity inferred from description of particle size distribution, matrix, sorting) and review of literature describing porosity versus texture (Dunne, and Leopold, 1978), I assume that cohesive valley fills have bulk density value's intermediate between hillslope and gravel delta deposits.

Valley fills were typically covered by mature second-growth conifers ≥ 80 years old when trees were cored in the fall of 1987. Many valley fills also have old-growth stumps present in growth position, suggesting these fills were deposited hundreds of years ago. Position and bank heights (terrace deposits are usually 1 to 2 meters above the channel thalweg) and volume of valley fills (19,000 m^3) suggest valley fills are much less mobile than deposits within the active channel (streambed, bar, debris jam).

Hillslope

As hillslopes abut some streambanks, it was also necessary to characterize particle size distribution and bulk density of hillslope deposits. Bulk density and particle size distribution estimates for hillslope deposits are presented in Table 11. These are developed from data collected for Caspar Creek basin by Wosika (1981). I used Wosika's data for samples located in inner gorge settings within 100 meters of the mainstem channels of North and South Fork Caspar Creek. All of these sites are mapped as Dehaven-Hotel Complex (MRCS, in press). I believe these sites match most hillslopes defining streambanks along mainstem North Fork Caspar Creek.

2.4 SEDIMENT STORAGE RESERVOIRS

I grouped mainstem channel and valley landforms into three sediment storage reservoirs based upon relative mobility and sediment source characterizations: active channel (AC), non-cohesive terrace (nT), and cohesive terrace (cT). AC reservoir includes debris jam, streambed, and bar map units. These deposits are grouped into the active channel reservoir because they have the following similarities:

1) the deposits are unvegetated or covered by water-loving shrubs and grasses or occasionally by small-diameter conifers, which suggests recent deposition and/or frequent mobilization (similar age distribution and relative mobility);

TABLE 11. PARTICLE SIZE DISTRIBUTION AND BULK DENSITY FOR HILLSLOPE DEPOSITS

Soil Pit*	Distance from Channel (km)	Profile Depth Sampled (m)	Bulk Density (kg/m³)	Gravel %	Sand %	Silt & Clay %
Hugo Pit # 3	0.1	0.2	1.12	19.8	39.6	40.6
Hugo Pit # 4	0.1	1.0	1.42	18.5	31.6	49.9
Ilugo Pit # 5	0.1	0.1	1.29	30.0	36.9	33.1
Ilu go Pit # 8	0.1	0.5	1.08	39.0	28.0	33.0
		Mean:	1.23	26.83	34.03	39.15
		Range:	1.08 to 1.42	18.5 to 39.0	28.0 to 39.6	33.0 to 49.9
		Best Estimates:	1.23	26.83	34.03	39.03

*Soils were mapped as Hugo Series when Wosika sampled hillslopes in 1981. NRCS (unpublished mapping) has since re-mapped these as Dehaven-Hotel Complex.

2) particle size distributions are similar - 75 to 81 percent gravel, 18 to 21 percent sand, and less than 1 percent fines.

3) position and elevation are similar - all streambed, bar, and debris jam deposits are over-topped by common to large storm flows (recurrence intervals of < 1 yr. to 6 yr.).

As I did not sample bulk density of streambed, bar, or debris jam deposits, I have assumed that North Fork Delta bulk density (USDA Forest Service, unpublished data) is representative. This is an important limitation. If bulk density of active channel deposits varies significantly over a wide range or is significantly different from delta values, estimation of mainstem channel storage changes (as mass) will be poor. I believe that all active channel deposits have similar bulk density, as streambed, bar, and debris jam deposits have similar particle size distribution. Gravel delta deposits, however, have a much larger percentage sand plus fines (39 percent) than streambed (19 percent), bars (18 percent), and debris jams (25 percent). This suggests bulk density of active channel deposits may be somewhat less than gravel delta bulk density.

I calculated particle size distribution for the active channel reservoir (AC) by a weighted average, where debris jam particle size distribution is weighted by the fraction of active channel area in debris jam; particle size distribution for the remaining fraction (bar and streambed area) is assumed equal to the average of bar and streambed. Particle size distribution and bulk density for AC is presented in Table 12.

Valley fills are subdivided into two sediment source types, non-cohesive fills and cohesive fills, based upon bank sedimentological descriptions. Estimates of erosional product from cohesive valley fills (in terms of mass by particle sizes) are probably less accurate than those for the active channel, and would probably be improved by further sampling. I believe my estimates for particle size distribution and bulk density for non-cohesive valley fills are fairly accurate, because these deposits are fluvial and similar to active channel deposits sampled. This is encouraging because nT represents approximately 65 percent of terrace volume and 77 percent of terrace bank length (Table 13).

2.5 CONCLUSIONS

1) As a result of detailed geomorphic mapping (1:370) and surveying, vegetation description, and visual distinction of differences in surface bed particle size, I delineated streambed, bar, debris jam, and terrace map units.

2) 24,000 m^3 of sediment is stored over the 2400 m study reach (10 m^3/m), 80 percent of which is in valley fill terraces.

Map Unit	Bulk Density (tonnes/m3)	% of AC area	% Gravel	% Sand	% Silt and Clay
Debris Jam	1.83	21.05	74.63	25.32	0.05
Bar/Streambed*	1.83	78.95	81.55	18.22	0.23
AC**	**1.83**	**100.00**	**80.09**	**19.71**	**0.19**

* Bar and streambed values are nearly identical (Table 2). Bar/streambed = mean of bar and streambed value.

* * AC values are developed from an average weighted by percent of active channel area (e.g., debris jam values are multiplied by 0.21 and bar/streambed by 0.79).

TABLE 13. DISTRIBUTION OF COHESIVE (cT) AND NON-COHESIVE (nT) TERRACE DEPOSITS

	(nT) bank length meters	(nT) volume m^3	(cT) bank length meters	(cT) volume m^3	(H) bank length meters	total bank length meters
Reach A	155-1	8980	40	250	642	2236
length = 1118 m						
Reach F	528	2660	422	5000	440	1390
length = 695 m						
Reach L	357	730	255	1570	568	1180
length = 590 m						
totals:	**2439**	**12370**	**717**	**6820**	**1650**	**4806**

Footnotes:
(H), hillslope; (cT), cohesive terrace; (nT), non-cohesive terrace..

total bank length = 2 x reach length along channel centerline

3) Active channel storage (streambed, bar, and debris jam) is roughly uniform over the three sediment routing reaches; it varies between 1.8 m^3/m in F to 2.4 m^3/m in A.

4) Bar sediment storage equals 975 m^3. Sixty-four percent of sediment stored as bars is in actively or recently aggrading and widening channel reaches that are adjacent to recent and recovered slide scars, tributary junctions, and former debris jams. 15 percent is associated with LWD not forming jams, and only a small fraction of bar storage is associated with alluvial features (21 percent).

5) Comparison of surface and subsurface streambed layers demonstrates that the surface layer is well armored (Table 2). The well-armored surface layer indicates that current rates of sediment delivery are much below bedload sediment transport capacity, and therefore, the streambed could accommodate an increase in sediment supply simply by textural change (bed surface fining) without substantial modification in bed topography or sediment storage (Dietrich, 1989). If this is the case, analysis of recent channel changes at cross-sections over streambed deposits should reveal little net-change in sediment storage.

6) Total volume of debris jam deposits is 710 m^3 (Table 4). Cumulative debris jam storage volume increases in a uniform fashion, however there is a marked contrast in spatial distribution and mean storage capacity of debris jams above and below the confluence of tributary D. These differences occur because mean channel width decreases above D making it is easier for pieces of debris to wedge between banks above D. Therefore large jams formed by accumulation of floated debris are rarer above D and small jams more common.

7) Analysis of debris jam sediment storage changes during WY 1985-1987 suggests that sediment stored in many jams is frequently mobilized and that some jams may be short-lived features (Table 7). Field observations and review of LWD maps show that uncut old-growth size LWD ($d \geq 1$ m) is not present in the channel today. Where old-growth pieces form jams they are contributed from the collapse of nearby logging structures, such as the old aerial tramway at the mouth of Tributary D.

8) Terrace storage varies considerably over the three reaches. It is much greater in reaches A (8.3 m^3/m) and F (11.0 m^3/m) than in L (3.9 m^3/m). Much lower volume per meter length in L may be related to steeper channel slope and narrower valley width in L (Table 1) which could cause a greater portion of

sediment delivered to the reach to be transported through. Terrace storage is highest in F (11.0 m^3/m), and if storage over reaches F and L is considered together (7.8 m^3/m), it is similar to storage per meter over reach A (8.3 m^3/m).

9) Three types of terrace deposits are present above Tributary D: fluvial, debris flow, and probable hyper-concentrated flow deposits. Below D, nearly all deposits are fluvial. Presence of old-growth stumps in growth position on many terrace surfaces suggests that these are many hundreds of years old. The largest concentration of terrace storage occurs at and just downstream of tributary junctions (as at Tributaries B, C, D, G, H). Terrace deposits in these locales include fans at mouths of tributaries, and an increase in the thickness of deposits in the downstream vicinity of the tributary junction.

10) Particle size distribution estimates for streambed, bar, and debris jam, and non-cohesive terrace (fluvial) deposits are all similar: gravel content ranges from 75 to 81 percent, sand is 17 to 25 percent, and fines are 0 to 3 percent.

11) 1 used previous sampling for hillslope particle size distribution (Wosika, 1981) to estimate particle size distribution for cohesive terrace deposits. Bank sedimentological description and review of Costa (1988) suggest that most

cohesive terrace deposits are debris flow deposits. Benda and Dunne (1987) suggest that hillslope and cohesive terrace particle size distribution should be similar.

12) Differences in position and elevation of deposits, vegetation age, volume of deposits, and sediment source characteristics were distinguished to define three sediment storage reservoirs: a) active channel, which includes streambed, bar, and debris jam deposits; b) non-cohesive terrace, and c) cohesive terrace deposits. Most active channel deposits can be frequently mobilized (scoured by flows with recurrence intervals of < 1 yr to 6 yr.). In contrast, most terrace deposits are infrequently mobilized as evidenced by vegetation age (most have mature second-growth conifers to 80 years old and some have old-growth stumps), and bank heights (typically 1 to 2 m above the channel bed). Non cohesive and cohesive deposits are distinguished as separate sediment storage reservoirs, as bank sedimentological descriptions suggest their particle size and bulk density are significantly different.

CHAPTER 3: ACTIVE CHANNEL STORAGE CHANGES, MAINSTEM SEDIMENT PRODUCTION, AND WATERSHED YIELD

3.1 INTRODUCTION

Sediment storage descriptions and analyses, presented in Chapter 2, are the basis for grouping mainstem channel deposits into sediment storage reservoirs: landforms of similar sediment source type (particle size distribution and bulk density) and relative mobility (frequency of erosion and transport). I used three sediment reservoirs to estimate mainstem channel sediment storage changes in terms of mass by particle size class (gravel, sand, fines).

Sediment storage changes in the mainstem channel, sediment production from bank erosion along the mainstem channel, and watershed yield are quantified and analyzed in this chapter by a sediment budget (mass balance) approach to determine controls on channel changes during a nine-year baseline period (WY 1980-1988) prior to second-growth logging, so that effects of logging can be evaluated by comparison to the baseline period.

3.2 WATERSHED SEDIMENT YIELD

Overview

Watershed sediment yield includes suspended-load and bedload fractions. My estimates of bedload yield are for that fraction of total yield with an intermediate particle diameter

≥1.4 mm (gravel and very coarse sand). Finer sand is sometimes also transported as suspended load under flow conditions that are common on the Mainstem North Fork Caspar Creek (Tom Lisle, personal communication). Consistent with my definition of bedload transport, I consider transport of particles < 1.4 mm as suspended load. Estimation of bedload transport rate in steep gravel-bed streams is often very poor because: 1) external sediment supply (e.g., sediment delivered directly from adjacent hillslopes) often represents a large portion of the sediment available for transport; and 2) continuous measurement during high flows presents numerous technical, logistical, and safety challenges. Therefore I estimated bedload yield by three independent approaches: 1) using WY 1988 bedload transport data, as measured at gauging station A by Birkbeck pit samplers (USDA Forest Service, unpublished data); 2) using the Meyer Peter-Mueller (1948) bedload transport equation; and 3) from USDA Forest Service data describing sedimentation in the North Fork weir pond.

Detailed measurements of suspended sediment transport during WY 1980-1988 were collected at the North Fork weir as part of the cumulative effects study now in progress (USDA Forest Service, unpublished data). Data describing suspended sediment yield at the North Fork weir outlet during WY 1986-1988 have been processed; however data describing suspended sediment yield for WY 1980-1985 is not yet available (Jack

Lewis, personal communication). Therefore I estimated average annual suspended-load yield for WY 1980-1985 by estimating the ratio between bedload and suspended-load yield for WY 1963-1976 when suspended sediment yield and North Fork weir pond sedimentation (volume, particle size, bulk density) were measured (Rice et al., 1979). 1 believe this approach is reasonable because estimated suspended-load and bedload ratio varied little during WY 1963-1976 (4.8:1 to 8.2:1) and this range is similar to the estimated ratios for WY 1986-1988 (3.4:1 to 8.6:1).

Estimation of Average Annual Bedload Yield Using Weir Pond Sedimentation Data

I estimated average annual bedload yield (mass/yr.) during WY 1980-1988 from: 1) annual surveys of weir pond sedimentation volume (USDA Forest Service, unpublished data); 2) sediment sampling in the summer of 1980 that describes bulk density and percent gravel of weir pond deposits (USDA Forest Service, unpublished data); and 3) sediment sampling in the summer of 1988 to describe particle size distribution of the gravel delta that forms at the upstream end of the weir pond.

As I do not have data describing particle size and bulk density of weir pond deposits at the end of the monitoring period, I assume that particle size (percent gravel) and bulk density data collected in the summer of 1980 also accurately describes weir pond deposits in the summer of 1988 (Table 14). 1 believe this is a reasonable assumption, as

TABLE 14. PARTICLE SIZE DISTRIBUTION AND BULK DENSITY FOR WEIR POND DEPOSITS

POND BULK DENSITY

Cross-section Reach	Bulk density (tonnes/m3)	Weight proportion*	Contribution to Weighted Mean Bulk Density
I 00-105	1.27	0.02	0.02
105-120	1.06	0.05	0.05
120-135	1.10	0.05	0.06
I 35-150	1.19	0.05	0.06
150-160	1.14	0.03	0.04
160-175	I .05	0.05	0.05
175-185	1.05	0.03	0.04
185-200	1.04	0.05	0.05
200-215	I .08	0.05	0.06
215-232	1.24	0.06	0.07
232-250	1.26	0.06	0.08
250-270	1.18	0.07	0.08
270-285	1.25	0.05	0.06
285-300	1.58	0.05	0.08
300-315	1.80	0.05	0.09
315-323	1.71	0.03	0.05
323-333	1.58	0.03	0.05
333-343	1.80	0.03	0.06
343-355	2.03	0.04	0.08
355-360	1.99	0.02	0.03
360-370	2.00	0.03	0.07
370-380	1.90	0.03	0.07
380-390	1.112	0.03	0.06
		Weighted Mean density(kg/m3) =	1.38

POND GRAVEL PERCENTAGE

Cross-section Reach	% Gravel (≥ 2mm)	Weight proportion*	Contribution to Weighted Mean Percent Gravel Value
100-105	3.08	0.02	0.05
105-120	3.37	0.05	0.17
120-135	4.36	0.05	0.23
135-150	9.74	0.05	0.50
150-160	12.00	0.03	0.41
160-175	10.89	0.05	0.56
175-185	10.90	0.03	0.38
185-200	7.58	0.05	0.39
200-215	8.23	0.05	0.43
215-232	10.73	0.06	0.63
232-250	8.15	0.06	0.51
250-270	9.51	0.07	0.66
270-285	18.17	0.05	0.94
285-300	36.68	0.05	1.90
300-315	50.58	0.05	2.62
315-323	59.02	0.03	1.63
323-333	64.75	0.03	2.23
333-343	65.22	0.03	2.25
343-355	66.85	0.04	2.77
355-360	63.04	0.02	1.09
360-370	60.38	0.03	2.08
370-380	60.46	0.03	2.08
380-390	53.76	0.03	1.85
		Weighted Mean %Gravel =	26.36

NOTES AND FOOTNOTES:

1. Sampling was in the Summer of 1980; Reach numbers correspond to cross-section locations in feet upstream of the weir.

*Each reach covers a portion of the pond. For example reach 100-105, 'covers 5 of 290 ft, and therefore, its weight proportion = 5/290 = 0.02

particle size distribution estimated from summer 1988 sampling of North Fork delta deposits is nearly identical to values estimated from summer 1980 sampling (Table 3). Tributaries X-Y-Z (drainage area = 1 km^2) join the mainstem channel in the North Fork weir pond, a short distance downstream of station A (Figure 1). I did not include these tributaries in the sediment budget study as they were logged in 1985 and 1986. However because tributaries X-Y-Z drain into the weir pond, weir pond sedimentation reflects contributions from both the study area above station A and from watershed X-Y-Z. As no unvegetated alluvial fans or bars were evident at the mouth of X-Y-Z during my fieldwork in the summers of 1987 and 1988, I assume that second-growth logging did not substantially increase bedload yield from X-Y-Z during the study period, and therefore, I believe that average weir pond sedimentation rate per km^2 accurately approximates relative yields from the both the study area and

tributaries X-Y-Z. Jack Lewis, a hydrologist at the USDA Forest Service Redwood Sciences Lab, has tabulated the results of annual surveys of weir pond sedimentation during WY 1978-1993, and I present this data in Table 15. Estimation of annual sedimentation in some dry years does not appear to be highly accurate, as indicated by zero totals or negative sedimentation results for some dry years (WY 1981, WY 1991, WY 1992). Review of annual sedimentation estimates suggests, however, that most

TABLE 15. NORTH FORK CASPAR CREEK WEIR POND SEDIMENTATION: WATER YEARS 1978-1993 (USDA Forest Service, unpublished data)

water year	pond capacity (m3)	deposited volume (m3)
1978	3928.9	
1979	3599.3	329.6
1980	3541.8	57.5
1981	3541.7	0.1
1982 a	3376.7	165
1982 b	4362.4	pond dredged
1983	3902.7	459.7
1984	3727.4	175.3
1985	3682.3	45.1
1986	3602.5	79.8
1987	3566.3	36.2
1988 a	3548.3	18
1988 b	4156.7	pond dredged
1989	4104.1	52.6
1990	3917.5	186.6
1991	3 942.2	-24.7
1992	3976.9	-34.7
1993	3606.5	370.4

footnotes:

19XX a,b: a signifies pond capacity (before) dredging which occurs later in same year (XX); b signifies pond capacity (after) dredging.

weir pond sedimentation occurs during very wet years, and therefore, poor estimates of dry year sedimentation probably will not cause large errors in estimating the cumulative sedimentation over WY 1980-1988, which includes two very wet years (WY 1982-1983).

Utilizing estimated cumulative sedimentation volume during WY 1980-1988 and 1980 particle size[2] and bulk density data, I estimate average annual gravel ($\geq$ 2 mm) yield from the North Fork Watershed during WY 1980-1988 at approximately 8.7 tonnes/km^2/yr (Table 16). Bedload yield should be slightly greater, as I have defined bedload as watershed sediment yield with intermediate particle diameter $\geq$ 1.4 mm (gravel and very coarse sand).

In the summer of 1988, bulk subsurface sediment samples were collected to describe the particle size distribution of North Fork delta deposits. The North Fork delta forms at the upstream end of the weir pond primarily by deposition of bedload, but also from settling of some sands from suspension. Assuming that almost all bedload delivered to the weir pond is deposited within the delta, and a much smaller fraction is deposited

[2] particle size data collected in 1980 only distinguishes percent gravel and fines (sand, silt, clay). Therefore using this data together with the weir pond cross-section data, I can only estimate yields of gravel and fines.

TABLE 16. ESTIMATATION OF AVERAGE ANNUAL BEDLOAD YIELD USING WEIR POND SEDIMENTATION DATA (USDA Forest Service, unpublished data)

Water Year	Peak Flow R.I. (yrs)	Percent of Mean Annual Rainfall	Pond Sedimentation Pond Sedimentation (m^3)	Gravel Yield (tonnes)	Bedload Yield (tonnes)	(tonnes)
1980	3	108	58	79	21	23
1981	1.1	66	0	0	0	0
1982	3.9	145	165	228	60	65
1983	6.8	182	460	634	167	180
1984	1.6	116	175	242	64	69
1985	2.5	68	45	62	16	18
1986	2.1	104	80	110	29	31
1987	1.1	78	36	50	13	14
1988	1.5	80	18	25	7	7
		Total:	1037	1431	377	406
		Annual Mean (tonnes):	115	159	42	45
		Annual Mean (tonnes/km²):			9	9

* measured sedimentation volume = - 5.7 cubic meters. I have assumed that actual sedimentation ~ 0 cubic meters

in deeper water closer to the outlet, the ratio of North Fork delta particles ≥1.4 mm to those ≥ 2 mm should give a good indication of bedload yield (≥ 1.4 mm) versus gravel yield (≥ 2 mm). For delta deposits sampled in the summer of 1988, the ratio of particles with intermediate diameter ≥ 1.4 mm to those ≥ 2 mm was 1.08:1. Therefore from North Fork delta particle size data and North Fork weir pond sedimentation data, I estimate that average annual bedload yield during WY 1980-1988 was 9.3 tonnes/km²/yr (9.3 tonnes per km² per year = 1.08 x 8.7 tonnes per km² per year).

Estimation of Average Annual Bedload Yield Using Birkbeck Pit Sampler Data

I also estimated bedload yield using WY 1988 bedload transport data measured by Birkbeck pit samplers (USDA Forest Service, unpublished data) at Station A. Four Birkbeck pit samplers (Reid et al. 1980) were installed at Station A in the fall of 1987 to monitor bedload transport. Each pit is a cast concrete cube with 0.6 m sides and a slotted metal cover that is 0.1 m wide and 0.4 m long in the direction of flow, and flush with the streambed. The sum of the widths of the four slot openings (0.4 m) is equal to 9 % of channel width at A.

Synchronous bedload transport rates measured at each pit are highly variable, and therefore, I have calculated transport by summing the accumulated mass deposited in the four pits during discrete transport periods. I have defined discrete transport periods on graphs of cumulative bedload versus time (USDA Forest Service, unpublished data) by: 1) the time that transport is initiated at a pit (ti), 2) hydrograph peak, 3) the time that pits are emptied by a dredge, and 4) significant changes in the slopes of the cumulative bedload curves (change in the rate of accumulation). I developed a rating curve of bedload discharge versus stream flow during the discrete transport periods (Figure 13), and this curve along with flow duration data for station A are used to estimate average annual bedload yield during the WY 1980-1988 monitoring period. Average annual bedload transport estimated from Birkbeck pit sampler measurements and flow duration data is 23 tonnes/km^2/yr (Table 17). Estimated yield from pit sampler based rating curve is significantly limited, however, by a lack of any high or moderate flow data and a poor curve fit (R^2 = 0.44).

Estimation of Average Annual Bedload Yield Using Meyer-Peter Mueller Bedload Transport Formula

Given the difficulties of measuring bedload transport in natural settings, bedload transport rate is often estimated by empirically derived transport formulas developed

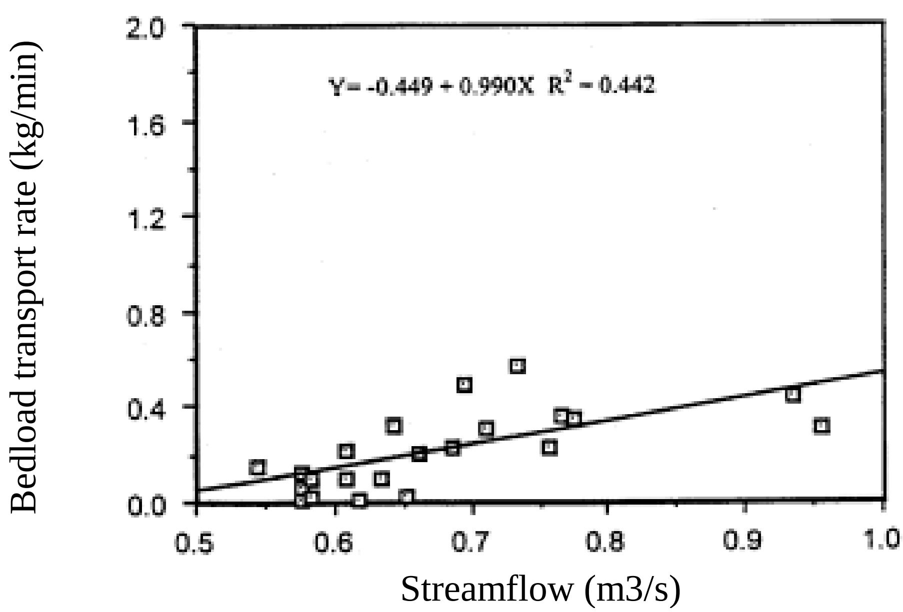

FIGURE 13. Rating curve of bedload transport rate using Birkbeck pit sampler data

TABLE 17. ESTIMATION OF AVERAGE ANNUAL BEDLOAD YIELD USING BIRKBECK PIT SAMPLER DATA

Streamflow (m^3/s)	*Transport Rate (t/day) (all particle sizes)	**Transport Rate (t/day) ($d \geq 1.4$ mm)	Fraction of Time	Bedload Yield (t/day)	
0.67	3.6	3.2	0.0040	0.01	
0.74	4.6	4.1	0.0034	0.01	
0.82	5.8	5.2	0.0041	0.02	
0.91	7.2	6.3	0.0029	0.02	
1.03	9.0	7.9	0.0029	0.02	
1.16	10.9	9.6	0.0022	0.02	
1.32	13.3	11.8	0.0017	0.02	
1.5	16.0	14.1	0.0009	0.01	
1.69	18.8	16.6	0.0010	0.02	
1.92	22.3	19.7	0.0009	0.02	
2.19	26.3	23.2	0.0008	0.02	
2.51	31.1	27.5	0.0004	0.01	
2.93	37.4	33.0	0.0005	0.02	
3.93	52.3	46.2	0.0003	0.01	
			Sum =	0.24	tonnes/day
			Bedload Yield =	23	tonnes/yr/km²

Footnotes:

transport rate (t/day)=1.44(-4.4603+10.379*streamflow(m3/s)): $R^2 = 0.44$

** estimated from proportion of sample ≥ 1.4 mm collected in pits for the storm of 3/10/89.

under controlled conditions in laboratory flumes. I utilized the Meyer-Peter Mueller (1948) bedload transport formula because It was developed under energy gradient, stream flow, and particle size conditions similar to those at gauging station A on the North Fork Caspar Creek (Table 18).

In applying the Meyer-Peter Mueller formula, I utilized reach-wide or cross-section mean values to define hydraulic parameters (slope, depth, velocity, roughness) input to the formula. This simplification, the importance of external sediment supply, and the presence of a "coarse bed cover-layer" at North Fork Caspar Creek may significantly reduce the accuracy of bedload yield estimated by this and other bedload transport formulae (Carson and Griffiths, 1987). Average annual bedload yield estimated using the Meyer-Peter Mueller bedload transport formula is 13 tonnes/km^2/yr (Table 19).

<u>Discussion of Bedload Yield Estimates</u>

Average annual bedload yield was estimated by three independent approaches: 1) North Fork weir pond sedimentation (9 tonnes/km^2/yr); 2) Birkbeck pit sampler (23 tonnes/km^2/yr); and 3) Meyer-Peter Mueller bedload transport formula (13 tonnes/km^2/yr). Considering the challenges inherent in estimating bedload yield, these estimates are quite close and they suggest that average annual bedload yield was

TABLE 18. COMPARISON OF NORTH FORK CASPAR CREEK TO MEYER-PETER MULLER FLUME

Channel	Slope (m/m)	Unit Discharge (m^3/sec/m)	Particle Size # (mm)	Qedload Transport Rate (tonnes/day)
Meyer-Peter Muller Flume	0.004 - 0.030	0.002 - 1.9	3.0 - 28.6	0 - 70
North Fork Caspar Creek	0.014	0.2 - 0.9 *	19.5 (d50)	0 - 50 **

Footnotes:

Meyer-Peter Muller Flume: uniform grain size mixtures over the indicated range

* lower limit from measurement in pit samplers at A; upper limit equals peak flow during WY 1980-1988

** transport rates inferred from instantaneous rates measured in pit samplers at A

TABLE 19. ESTIMATION OF AVERAGE ANNUAL BEDLOAD YIELD USING MEYER-PETER AND MULLER EQUATION (I 948)

North Fork Caspar Creek at Flume A

sp gr sediment	2.65	a=4.42	k=0.6150
Dmean (m)	0.01950	b=0	m=0.62
D90 (m)	0.06875	c=0.366	a*c*k=0.995
Kr	40.62	f--0.355	b+f+m=0.976

Streamflow (m^3/s)	width (m)	depth (m)	velocity (m/s)	slope (m/m)	Km	u* (m/s)	Xb (kg sed/ kg w)	bedload Yield (t/day)	% of time	tonnes/day
0.82	4.42	0.34	0.54	0.014	9.39	0.217	0.00000	0	0.0040	0.00
0.91	4.42	0.35	0.58	0.014	9.86	0.220	0.00000	0	0.0027	0.00
1.03	4.42	0.37	0.62	0.014	10.21	0.226	0.00000	0	0.0031	0.00
1.16	4.42	0.39	0.67	0.014	10.65	0.232	0.00000	0	0.0024	0.00
1.32	4.42	0.40	0.73	0.014	11.33	0.235	0.00000	0	0.0016	0.00
1.50	4.42	0.42	0.79	0.014	11.86	0.241	0.00000	0	0.0013	0.00
1.69	4.42	0.44	0.85	0.014	12.41	0.247	0.00000	0	0.0009	0.00
1.92	4.42	0.46	0.92	0.014	13.03	0.252	0.00000	0	0.0008	0.00
2.19	4.42	0.48	1.00	0.014	13.74	0.258	0.00000	0	0.0007	0.00
2.51	4.42	0.51	1.09	0.014	14.36	0.266	0.00000	0	0.0004	0.00
2.93	4.42	0.54	1.20	0.014	15.22	0.273	0.00022	57,	0.0004	0.02
3.93	4.42	0.60	1.44	0.014	17.11	0.287	0.00103	349	0.0003	0.12

tonnes/day= 0.14

tonnes/yr. = 51
tonnes/yr/km² = 13

quite low during the study period. Each of these approaches however have limitations which may effect their accuracy.

The Birkbeck pit sampler approach probably gives the poorest estimate of average annual bedload yield, as the rating curve I developed relied entirely on low-flow data (recurrence interval < 0.5 years), and extrapolation to estimate transport rate at higher flows. Also the bedload rating curve will shift in time, as 1) initial channel conditions affecting entrainment and transport of sediment (i.e., occurrence of coarse lag deposits, availability of easily mobilized sediment within the active channel); and 2) storm-specific variables (i.e., external sediment supply, water surface slope, etc.) may vary greatly over time.

Carson and Griffiths (1987) and Bathurst (1986) reviewed the performance of various bedload transport formula by comparison to actual yields where these were known for various streams. Based upon their reviews, I believe that the Meyer-Peter Mueller estimate of bedload yield, 13 tonnes per km^2 per year, is probably accurate within ± 100 percent of the true yield.

I believe the weir pond sedimentation analysis gives the most accurate of the three estimates of bedload yield as it is developed from annual measurement of closely

Spaced cross-sections (cross-sections are 5-to-20 feet apart); and 2) intensive sampling of particle size distribution and bulk density (3 samples at each of 24 weir pond cross-sections). The main uncertainty in this estimate relates to determining proportional contributions from the study area (DA = 3.83 km^2) and tributaries X-Y-Z (DA = 1.00 km^2). Even if all of the weir pond bedload yield came from the study area or from tributaries X-Y-Z, the possible range of estimated bedload yield for the study area would be within the range of 0-to-11.8 tonnes per km^2 per year (45 tonnes per year ÷ 3.83 km^2 = 11.8 tonnes per km^2 per year). As nearly 79 percent of the weir pond catchment area is above station A, I believe that actual contribution from the mainstem study area was ≥ 50 percent of total bedload yield. Therefore I estimate that average annual bedload yield from the study area during WY 1980-1988 was between 6 and 12 tonnes per km^2 per year; best estimate of actual yield is 9.3 tonnes per km^2 per year (9.3 tonnes per km^2 = 0.79 x 11.8 tonnes per km^2).

Suspended Yield

Suspended yield for WY 1986-1988 is estimated by Lewis (unpublished data). I estimated suspended sediment yield during WY 1980-1985 from analysis of:

a) suspended sediment yields at the North Fork Weir outlet during WY 1963-1976

(Rice et al., 1979); b) particle size and bulk density sampling of weir pond deposits in summer 1980 (USDA Forest Service Redwood Sciences Lab, unpublished data); and c) annual measurements of pond sedimentation volume (Rice et al., 1979) during WY 1963-1976. These data were considered together to estimate the ratio of bedload to suspended yield for WY 1963 through 1976. In this analysis, I assume 1980 particle size and bulk density results also accurately describe weir pond deposits during WY 1963-1976. Average annual suspended sediment yield (intermediate diameter < 1.4 mm) for the Water Year 1980 through 1988 period is estimated as approximately 60 tonnes per km^2 per year (Table 20).

Comparison to Estimates for Forested Basins Underlain by Competent Franciscan Assemblage

Annual sediment yields from North Fork Caspar Creek for Water Years 1980-1988 and 1963-1976 are summarized in Tables 20 and 21. I estimate total average annual sediment yield from North Fork Caspar Creek watershed as 69 tonnes per square kilometer per year during Water Years 1980-1988 and 262 tonnes per square kilometer per year for Water Years 1963-1976. I believe sediment yield during WY 1963-1976 was much higher because: a) very large floods occurred during WY 1965, WY 1966 and

TABLE 20. SEDIMENT YIELD FOR NORTH FORK CASPAR CREEK: WY 1980-1988

Water Year	Peak Flow R.I. (yrs)	Percent of Mean Annual Rainfall	Pond Sedimentation (m^3)	Pond Sedimentation (tonnes)	Bedload Yield (a) (tonnes)	Suspended Sediment (b) Yield (tonnes)
1980	3	108	58	79	23	145
1981	1.1	66	0	0	0	48.5 **
1982	3.9	145	165	228	65	416
1983	6.8	182	460	634	180	1160
1984	1.6	116	175	242	69	442
1985	2.5	68	45	62	18	114
1986	2.1	104	80	110	31	166
1987	1.1	78	36	50	14	47
1988	1.5	80	18	25	7	50
		Total:	1037	1431	406	2589
		Annual Mean:	115	159	45	288
		Annual Mean (t/km²):			9	60
		Average Annual Sediment Yield (t/km²):				69

Footnotes:
(a) bedload yield = 0.284 * pond sedimentation, from weir pond sampling in 1980 and 1988.
(b) watershed suspended sediment yield WY 1980-1985 = 6.44 * estimated bedload yield; assumes average ratio for WY 1963-1976 also applies to WY 1980-1985. Watershed suspended sediment yield for WY 1986-1988 (USDA Forest Service, unpublished data)

** I assume that WY 1981 yield = WY 1987-1988 average

TABLE 21. SEDIMENT YIELD FOR NORTH FORK CASPAR CREEK: WY 1963-1976

Water Year	Peak Flow R.I. (yrs)	Percent of Mean Annual Rainfall	Pond Sedimentation (m^3)	Pond Sedimentation (tonnes)	Bedload Yield (a) (tonnes)	Suspended Sediment (b) Yield (tonnes)
1963	1.3	97	80	111	31	224
1964	1.7	70	91	126	36	224
1965	9	104	978	1349	383	1840
1966	27	84	1180	1629	463	2228
1967	1.4	107	86	118	34	282
1968	1.4	81	77	106	30	172
1969	3.4	101	562	776	220	1112
1970	2.7	99	324	447	127	873
1971	4.5	108	530	732	208	1223
1972	1.2	74	- I 14 *	0	0	73
1973	1.9	111	257	354	101	719
1974	27	146	1739	2400	682	5581
1975	2.3	105	340	469	133	896
1976	1.2	67	-50 *	0	0	75
		Total:	6081 (2)	8391	2383	15359
		Annual Mean:	434	599	170	1097
		Annual Mean in (tonnes/km^2):			35	227
		Average Annual Sediment Yield (tonnes/km^2):				262

Notes:
Water Year 1963-1976 sedimentation and suspended sediment yield from Rice (1979).
All other data (USDA Forest Service, unpublished data)
Footnotes:
* I assume actual sedimentation was approximately 0.
(a) bedload yield = 0.284 * pond sedimentation, from weir pond sampling in 1980 and 1988.
(b) NFCC watershed suspended sediment yield WY 1963-1976 = (Pond sedimentation + suspended sediment yield at outlet) - bedload yield

WY 1974 (the WY 1966 and WY 1974 peak flow events had 27 year recurrence intervals); and b) a 3300 cubic meter slide mass was delivered directly to reach L during the WY 1974 peak flow event, and much of this was transported to the weir pond during the March 1974 storm (Rice et al., 1979).

Estimates of total yield from North Fork Caspar Creek are comparable to estimates of approximately 100-to-300 tonnes per km^2 per year for other forested basins in competent Franciscan terrane where a substantial portion of the basin has been previously logged (Janda, 1972; Kelsey, 1980; Madej, O'Sullivan, and Varnum, 1986). This suggests sediment yield estimates for North Fork Caspar Creek are reasonable.

Given the objectives of this study, I am also interested in understanding how North Fork Caspar Creek sediment yield compares to similar streams in old-growth redwood forest. A limited amount of published data exists regarding suspended-load yield from streams in old-growth forests underlain by competent Franciscan terrane. Janda (1977) lists average annual suspended-load yields for two such streams in WY 1975-1976[2]: Hayes and Little Lost Man Creeks, both located in Redwood National Park. In WY 1975-1976, average annual suspended-load yields from Hayes and Little Lost Man Creeks

[2] There was a large flood in the Redwood Creek basin in water year 1975. This storm did not affect streams in Mendocino County. Water year 1976 was very dry throughout California.

were 14 and 26 tonnes per km^2 per year respectively. These amounts are about 14-to-26 percent of the amount measured at North Fork Caspar Creek in the same years. Lowest estimated annual suspended-load from North Fork Caspar Creek is 57 tonnes per km^2 in WY 1988 or about two-to-four times more than from Hayes and Little Lost Man Creeks in WY 1975-1976. This comparison suggests that nineteenth century logging may have caused a persistent increase in sediment yield from North Fork Caspar Creek. A longer period of record at these or other streams in old-growth would been needed, however, to draw definitive conclusions.

3.3 MAINSTEM CHANNEL CHANGES

Approach

I estimated sediment storage changes by measuring area(s) of net scour and/or net fill at 64 cross-sections established over the 2400 meter mainstem study reach by Tom Lisle in summer 1979. USDA Forest Service personnel resurveyed all of these in 1980 and 48 of these in 1986. I resurveyed 45 of them in 1988.

I also reviewed cross-section survey notes (1979, 1980, 1986, 1988), LWD maps (1984-1986), and geomorphic maps (1987) to determine when sediment storage changes occurred in the vicinity of LWD, recent landslide scars, channel meanders, and tributary junctions. I did this because, in describing mainstem sediment storage (Chapter 2), I had concluded that easily mobilized sediment in the active channel occurs in association with: a) LWD jams; and b) bars formed by LWD, recent slide scars, and tributary junction depositional controls. Elsewhere the streambed is typically well armored (Table 2) and therefore capable of accommodating an increase in sediment supply without substantial change in sediment storage (Dietrich, 1989).

At each cross-section, I used 1987 geomorphic maps, cross-section plots, and survey notes to delineate active channel, hillslope, cohesive terrace, and non-cohesive terrace reservoir boundaries. Changes in area were then calculated from cross-section survey data with Debris, a USDA Forest Service software package designed to plot channel cross-sections, compute net scour and net fill, and calculate hydraulic parameters. I adjusted calculation boundaries: a) to account for differences in surveying detail; b) to account for LWD pieces within the channel cross-section; and c) to correct for in-exact tie-in of some cross-section pins.

Because valley-fill terraces and hillslopes define the streambanks of mainstem North Fork Caspar Creek, I refer to terrace and hillsope deposits as these features as "streambanks" in the net scour and fill analyses. During the monitoring period

(WY 1980-1988), no overbank deposition was noted at cross-sections on existing terrace or hillslope streambanks, and no deposition of new terraces was noted either. Given typical terrace height above the streambed (1-to-2 m), at present, overbank deposition apparently is very infrequent or rare (Figure 14). Therefore, I consider all terrace and hillslope bank erosion as sediment production sources to the mainstem channel. Also, soils are not developed on the valley fills suggesting relatively recent isolation of valley fills. This change apparently has important ramifications for valley sediment-storage trends, mainstem channel routing, and basin yield. These issues are discussed in detail in Chapter 4. Section 4.4 (channel response to historical logging activities).

I estimated changes in sediment storage (as volume) by multiplying reservoir length by mean changes in cross-section area. Active channel length is determined by measuring length along the channel centerline; bank length is twice the centerline channel length. Bank classification as non-cohesive terrace, cohesive terrace, and hillslope was determined from geomorphic mapping and sedimentological descriptions of bank exposures. Sediment size data and change in storage volume were combined to estimate changes in sediment mass by grain-size categories (gravel, sand, fines) in three geomorphically defined stream reaches: A, F, and L (Table 1).

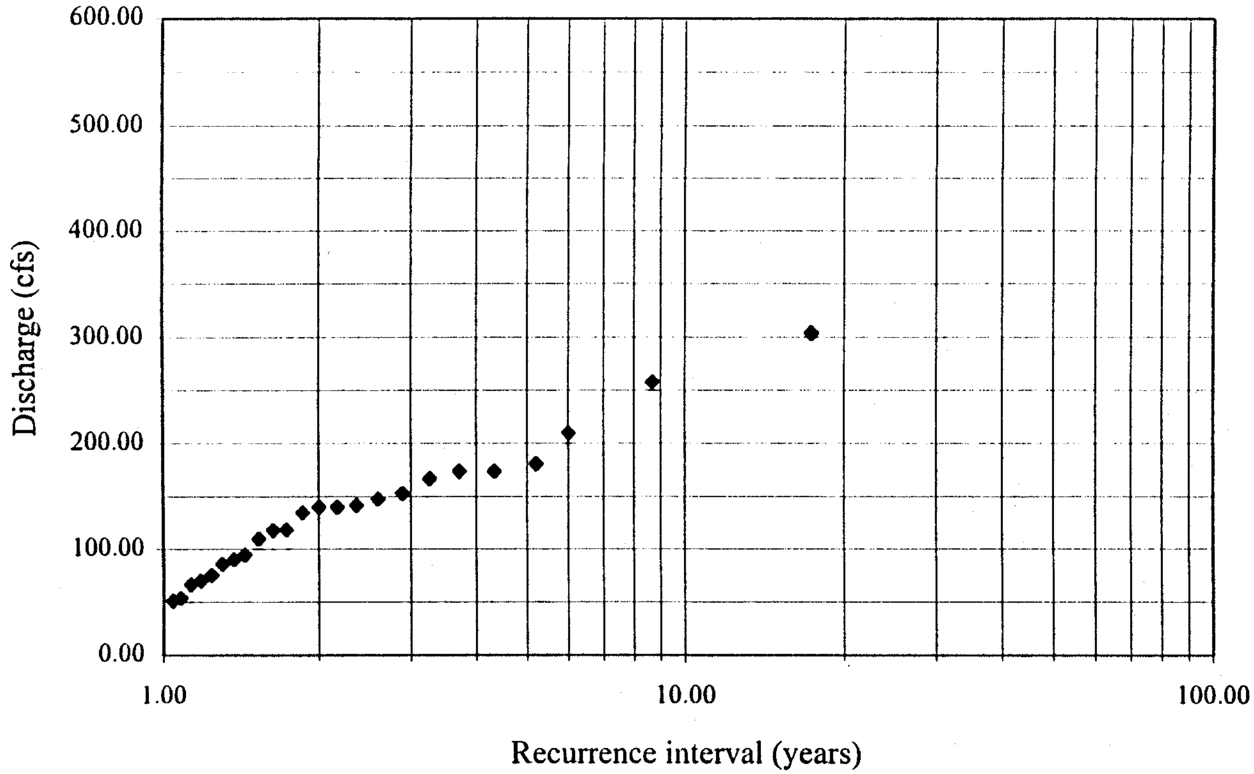

FIGURE 14. Flood frequency curve for North Fork Caspar Creek at weir outlet

Note: discharge of approximately 420 cfs would be needed to overtop a 1.0 m high terrace adjacent to station A.

3.4 CHANNEL CHANGES AND SEDIMENT PRODUCTION RESULTS

Changes in Sediment Storage

1) 70 to 100 percent of all net scour and fill, between cross-section surveys, occurred at 30 percent or less of all cross-sections (Table 22).

2) Most net scour and fill occurred in the active channel. Rates of active channel net scour and fill (Table 23) were typically an order of magnitude greater than rates of sediment production from streambank erosion (Table 24).

3) LWD, recent slidescars, and tributary junctions were where the vast majority of channel changes occurred: 60 to 80 percent of all net fill, and 80 percent of all net scour occurred at these features (Table 25). Elsewhere, the streambed is well-armoured and little change in storage occurred.

Channel storage changes and streambank sediment production in Reaches A, F, and L, estimated from cross-section and sediment sampling data, are presented in Table 26. The product of channel storage changes and bank erosion equates to the mainstem channel input (contribution) to basin sediment yield.

Water Year 1980

Change in Cross-section Area (dA) by Sediment Storage Reservoir

	(AC) Net Scour (m²/yr)	(AC) Net Fill (m²/yr)	(H) Net Scour (m²/yr)	(nT) Net Scour (m²/yr)	(cT) Net Scour (m²/yr)
Mean (dA) - all cross-sections:	0.12	0.09	0.02	0.01	0.02
mean (dA) - upper 30 percentile cross-sections:	0.34	0.21	0.16	0.12	0.12
percentage of total (dA) at upper 30 percentile cross-sections:	88.8	76.5	100.0	100.0	100.0

Water Years 1981-1986

	(AC) Net Scour (m²/vr)	(AC) Net Fill (m²/yr)	(H) Net Scour (m²/yr)	(nT) Net Scour (m²/vr)	(CT) Net Scour (m²/yr)
mean (dA) - all cross-sections:	0.04	0.04	0.01	0.01	0.01
mean (dA) - upper 30 percentile cross-sections:	0.10	0.10	0.03	0.03	0.04
percentage of total (dA) at upper 30 percentile cross-sections:	78.7	68.8	97.0	100	95.6

Water Years 1987-1988

	(AC) Net Scour (m²/yr)	(AC) Net Fill (m²/yr)	(H) Net Scour (m²/vr)	(nT) Net Scour (m²/yr)	(CT) Net Scour (m²/yr)
mean (dA) - all cross-sections:	0.02	0.02	0.01	< 0.01	< 0.01
mean (dA) - upper 30 percentile cross-sections:	0.09	0.09	0.02	0.04	0.02
percentage of total (dA) at upper 30 percentile cross-sections:	78.7	85.7	90.3	100	100

Notes:

AC: active channel; H: hillslope; nT: non-cohesive terrace; cT: cohesive terrace

Upper 30 percentile cross-sections: where change in area was greater than that measured at 70 percent or more of all cross-sections (i.e., if 10 cross-sections were surveyed, 'the 3 cross-sections with 'the greatest change in area would constitute the upper 30 percentile cross-sections).

Monitoring Period Summary of cross-sections where no measureable change in area was noted

WY 1980: 64 cross-sections were surveyed. and there no AC scour at 33 of these and no AC fill at 28 of these.

WY 1981-1986: 48 cross-sections were surveyed, and there was no AC scour at 16 of these and no AC fill at 11 of these.

WY 1987-1988: 45 cross-sections were surveyed, and there was no AC scour or AC fill at 31 of these.

TABLE 23. ACTIVE CHANNEL NET SCOUR AND FILL RATES

	Reach:	L	F	A
		(tonnes/m/yr)	(tonnes/m/yr)	(tonnes/m/yr)
Monitoring Period	Reservoir Scour/fill			
Water Year 1980	(AC) net till	0.115	0.089	0.197
	(AC) net scour	0.348	0.060	0.102
	net change	**-0.233**	**0.029**	**0.095**
Water Years 1981-1986	(AC) fill	0.068	0.044	0.067
	(AC) scour	0.061	0.057	0.038
	net change	**0.007**	**-0.013**	**0.029**
Water Years 1987-1988	(AC) till	0.0-13	0.009	0.038
	(AC) scour	0.027	0.046	0.032
	net change	**0.016**	**-0.037**	**0.006**

Notes:
1. AC: active channel

2. all changes are expressed in mass (metric tonnes) per year per unit stream reach length, where reach length is measured along the channel centerline.

3. minus sign (-) signifies net decrease in sediment storage

TABLE 24. STREAMBANK NET SCOUR RATES

Monitoring Period	Reach: Reservoir Scour/fill	L (tonnes/m/yr)	F (tonnes/m/yr)	A (tonnes/m/yr)
Water Year 1980	Streambank Scour	**-0.027**	**-0.009**	**-0.020**
Water Years 1981-1986	Streambank Scour	**-0.008**	**-0.029**	**-0.015**
Water Years 1987-1988	Streambank Scour	**-0.001**	**-0.008**	**-0.001**

Notes:

1. Streambanks include hillslope, cohesive and non-cohesive terrace deposits which abut the active channel.

2. minus sign (-) signifies net scour; no fluvial deposition was measureable on streambanks at channel cross-sections.

TABLE 25. CHANGES IN ACTIVE CHANNEL STORAGE ASSOCIATED WITH LWD, RECENT SLIDE-SCARS, TRIBUTARIES, AND ALLUVIAL FEATURES

Water Year 1980

Feature	AC Scour (m^2)	% of total AC Scour	AC Fill (m^2)	% of total AC Fill
LWD	2.4	30	1.7	30
Landslide	3.2	40	1.4	25
Tributary	0.7	9	0.6	11
Alluvial	0.2	2	0.3	5
Uncertain	1.5	19	1.6	28
Total:	8.0	100	5.6	too

Water Years 1981-1986

Feature	AC Scour (m^2)	% of total AC Scour	AC Fill (m^2)	% of total AC Fill
LWD	5.8	56	3.8	32
Landslide	2.3	22	3.5	29
Tributary	0.2	2	2.3	19
Alluvial	1.1	11	0.7	6
Uncertain	0.9	9	1.4	12
Other	0.0	0	0.2	2
Total:	10.3	100	11.9	100

Water Years 1987-1988

Feature	AC Scour (m^2)	% of total AC Scour	AC Fill (m^2)	% of total AC Fill
LWD	1.6	74	1.1	58
Landslide	0.0	0	0.1	5
Tributary	0.2	10	0.0	0
Alluvial	0.2	8	0.6	32
Uncertain	0.2	8	0.1	5
Total:	2.1	100	2.0	100

Other: refers to active channel scour associated with installation of a foot bridge.

TABLE 26. ACTIVE CHANNEL STORAGE CHANGES AND SEDIMENT PRODUCTION
FROM STREAMBANK EROSION: WATER YEARS 1980-1988

Reach 1.	**WY 1980**			**WY 1981-1986**			**WY 1987-1988**		
Reservoir Scour/Fill	Gravel (tonnes)	Sand (tonnes)	Silt-Clay (tonnes)	Gravel (tonnes)	Sand (tonnes)	silt-clay (tonnes)	Gravel (tonnes)	Sand (tonnes)	Silt-Clay (tonnes)
Active Channel (dS)	-138.4	-34.0	-0.3	25.9	6.4	0.1	18.8	4.6	0.0
Valley Fill (dS)	-14.5	-10.6	-10.7	-15.9	-10.6	-10.2	0.0	0 0	0.0
liillslupe (ds)	-1.3	-1.7	-1.9	-12.4	-15.7	-18.1	-0.6	-0.7	-0.8
Change in Storage:	**-I54.2**	**-16..3**	**-12.9**	**-2.4**	**-19.9**	**-28.2**	**18.2**	**3.9**	**-0.8**
Reach F	**WY 1980**			**WY 1981-1986**			**WY 1987-1988**		
Reservoir Scour/Fill	Gravel (tonnes)	Sand (tonnes)	Silt-Clay (tonnes)	Gravel (tonnes)	Sand (tonne)	Silt-C'Iay (tonnes)	Gravel (tonnes)	Sand (tonnes)	Silt-Clay (tonnes)
Active Channel (dS)	20.4	5.0	0.0	-57.0	-14.0	-0.1	-51.7	-12.7	-0.1
Valley Fill (dS)	-1.5	-1.8	-2.1	-I(11.9	-32.9	-19.9	-6.5	-2.1	-1.2
Ilillslupe (ds)	-5.0	-6.4	-7.4	-17.7	-22.5	-25.9	-4.8	-6.1	-7.0
Change in Storage:	**13.9**	**-3.2**	**-9.5**	**-176.6**	**-69.4**	**-45.9**	**-63.0**	**-20.9**	**-8.3**
Reach A	**WY 1980**			**WY 1981-1986**			**WY 1987-1988**		
Reservoir Scour/Fill	Gravel (tonnes)	Sand (tonne)	Silt-Clay (tonnes)	Gravel (tonnes)	Sand tonnes)	Silt-Clay (tonnes)	Gravel (tonnes)	Sand tonnes)	Silt-Clay (tonnes)
Active Channel (dS)	106.5	26.2	0.3	197.0	48.5	0.5	15.3	3.8	0.0
Valley Fill (dS)	-19.8	-4. I	-0.9	-94.1	-20.0	-4.5	0.0	0.0	0.0
hillslope (ds)	-3.0	-3.8	-4.4	-4.8	-6.0	-7.0	-1.3	-1.7	-1.9
Change in Storage:	**83.7**	**18.3**	**-5.0**	**98.1**	**22.5**	**- 11.0**	**14.0**	**2.1**	**-1.9**
Sediment Production;	**56.6**	**31.2**	**27.4**	**80.9**	**66.9**	**85.2**	**30.8**	**14.9**	**10.9**

Footnotes and Notes:
dS: change in storage, - sign implies net scour, no sign implies net fill
no net till was noted on valley fill and hillslopc "streambanks" during WY 1980-1988.
Active Channel includes floodplains, bars, debris jam deposits, and the streambed.

4) Principal mainstem-channel sediment inputs to basin yield during WY 1980-1988 were from net scour of the active channel in reach L during WY 1980 and in reach F during WY 1981-1986 and 1987-1988; and from streambank erosion in all reaches and periods between cross-section surveys.

5) most of the substantial decrease in storage in reach L during WY 1980 (173 tonnes per year) came from scour of a landslide that was deposited in reach L in 1974 (Figures 15 and 16).

6) Decreases in channel storage in reach F in WY 1981-1986 (12 tonnes per year) and WY 1987-1988 (32 tonnes per year) were primarily associated with LWD-related scour. Mechanisms included debris jam breaching and/or collapse, plunge pool erosion, and flow deflection and concentration by LWD not forming jams.

7) Streambank erosion (101 tonnes/yr. in WY 1980, 73 tonnes/yr. in WY 1981-1986, and 17 tonnes/yr. in WY 1987-1988) was associated with channel widening during debris jam tilling, and flow deflection toward banks by LWD. Streambank erosion was also associated with channel widening adjacent to

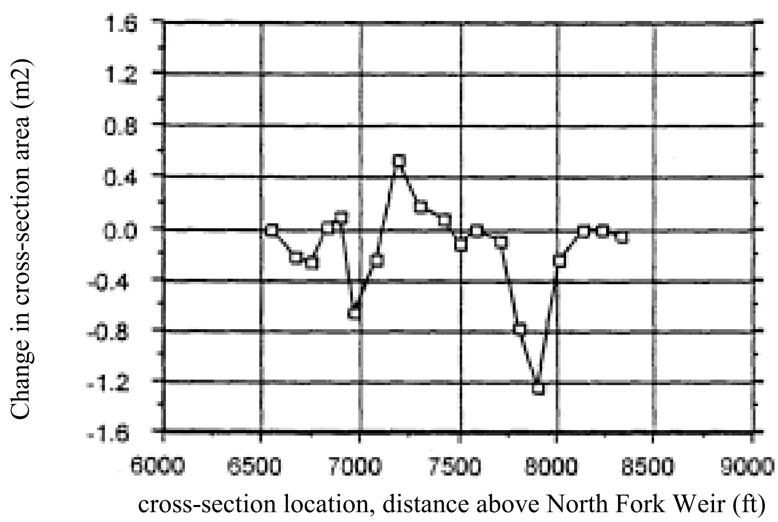

FIGURE 15. Net changes in active channel cross-section area in reach L during WY 1980

NORTH FORK CASPAR CREEK: CROSS-SECTION # 75

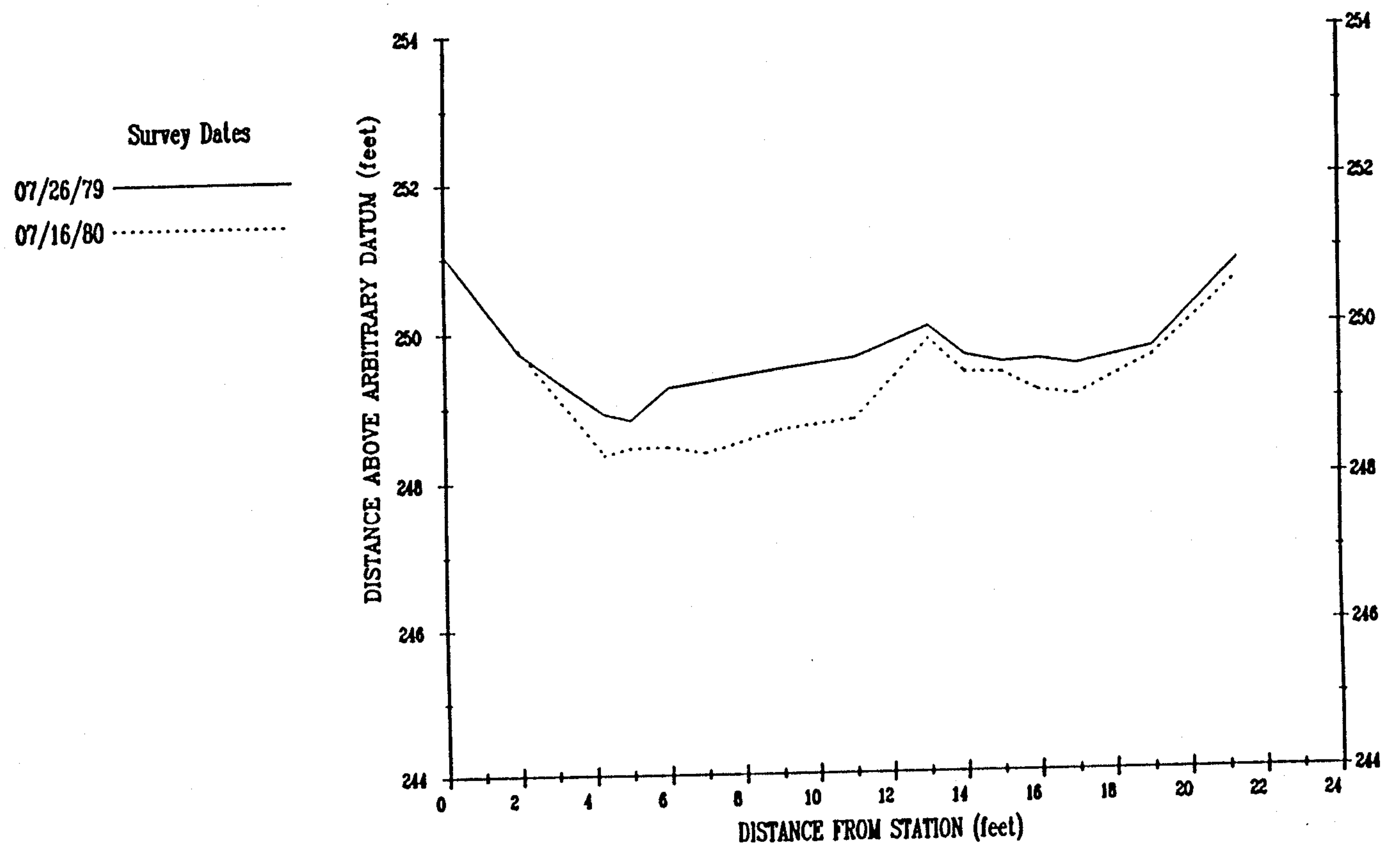

FIGURE 16. Net scour of active channel in reach L during WY 1980 adjacent to a recent slide-scar

recent landslide scars, deflection of flow at tributary junction alluvial fans, and erosion at outside bends. Substantially lower streambank erosion rate in WY 1987-1988 appears to be attributable to reduced frequency of high flows (Table 27).

8) Principal sediment sinks in WY 1980-1988 were in reach A throughout the study period, and in reach F during WY 1980. Channel storage increases in reach A during WY 1980 (133 tonnes per year) were primarily adjacent to a recent landslide scar (Figure 17), and at LWD jams (Figure 18); sediment storage increases in reach F during WY 1980 (25 tonnes per year) were in the vicinity of L WD pieces and jams, and near Tributary D.

3.5 ACTIVE CHANNEL STORAGE CHANGES, MAINSTEM SEDIMENT PRODUCTION, AND BASIN YIELD

Introduction

Active channel storage changes (e.g., streambed, bars, floodplains, and LWD jams) and sediment production from valley fill-and-hillslope bank erosion, estimated from cross-section and sediment sampling data, are presented in Table 26. For each period between

TABLE 27. FREQUENCY OF FLOWS CAPABLE OF BEDLOAD TRANSPORT AT GAUGING STATION A

Water Year: Mean of discharge interval at Station A (m^3/s) (1)	1980	1981	1982	1983	1984	1985	1986	1987	1988	Totals: (days)
	←		(amount of time in days where flows were capable of bed load transport)						→	
0.82	1.45	0.77	1.84	3.76	1.8	0.21	2.31	0.37	0.64	13.2
0.91	1.47	0.62	0.51	2.22	1.43	0.17	1.66	0.54	0.13	8.8
1.03	1.25	0.53	2.11	3.14	1.12	0.14	1.52	0.19	0.29	10.3
1.16	0.59	0.53	1.49	2.52	1.21	0.05	1.15	0.21	0.21	8.0
1,32	0.32	0	0.79	2.2	0.73	0.33	0.66	0	0.14	5.2
1.50	0.16	0	1.44	1.59	0.2	0.06	0.54	0	0.31	4.3
1.69	0.28	0	0.6	1.13	0.61	0.18	0.13	0	0.1	3.0
1.92	0	0	0.8	0.74	0.28	0.34	0.21	0	0.28	2.7
2.19	0.27	0	0.75	0.67	0.37	0.1	0.1	0	0.12	2.4
2.51	0	0	0.43	0.28	0.12	0.06	0.39	0	0	1.3
2.93	0.2	0	0.11	0.15	0.11	0.11	0.52	0	0	1.2
3.93	0.22	0	0.22	0.66	0	0.01	0	0	0	1.1
Q_b Days (2) =	6.2	2.5	1 1.1	19.1	8.0	1.8	9.2	1.3	2.2	61.3

Notes: (1) geometric mean of flow interval; streamflow measured in M^3/sec.
(2) estimated amount of time in days where flows was ≥ critical for bedload transport. 0.82 m3/s was selected as the critical flow at A, based upon review of initiation of transport and transport rate data for the pit sampler at A over Water Years 1987-1988.

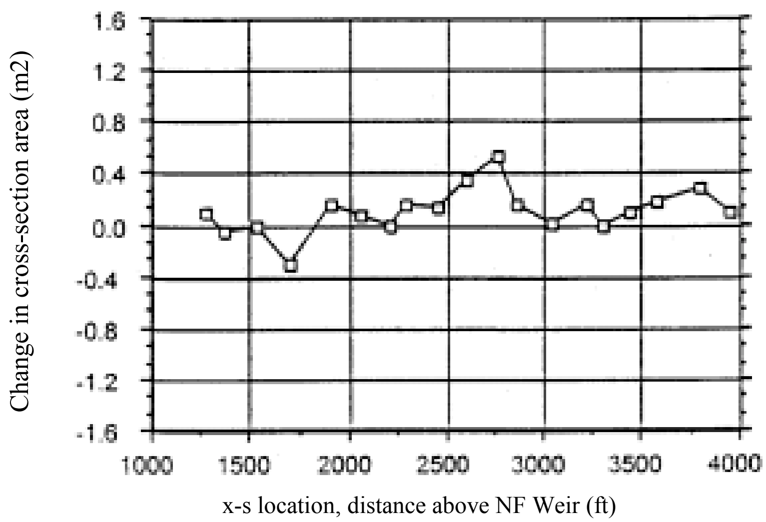

FIGURE 17. Net scour of the active channel in reach A during WY 1980: adjacent to recent slide-scar approximately 2600 to 2800 ft upstream of weir.

NORTH FORK CASPAR CREEK: CROSS-SECTION # 42

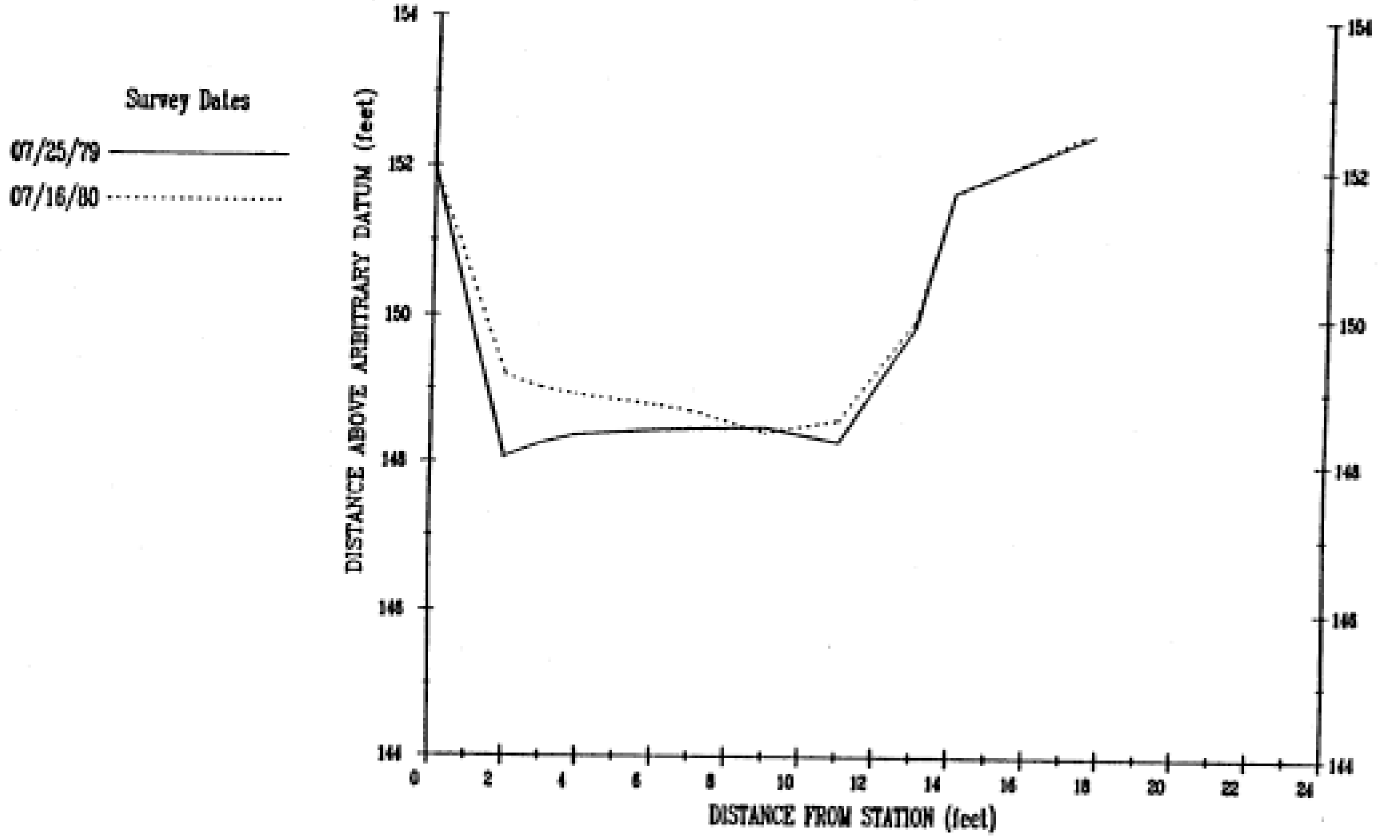

FIGURE 18. Net filling of active channel during WY 1980 at debris jam (O6)

cross-section surveys, the product of mainstem bank erosion plus active channel storage changes constituted an input (net contribution) to the basin sediment yield. In Table 28, mainstem channel input to basin sediment yield for each monitoring period is shown by grain-size category (gravel, sand, fines). Note that, for WY 1980 and 1987-1988, estimated mainstem channel gravel inputs to basin yield are greater than estimated total gravel yield from the basin - a physical impossibility. These discrepancies are probably best explained by two factors that cause mainstem channel gravel input to be overestimated: 1) a large proportion of greywacke gravels input to channels in North Fork Caspar Creek basin break down rapidly into finer particles (sand and fines) during fluvial transport; and 2) few channel cross-sections were located within backwaters of LWD jams, which are important sites for coarse sediment (sand and gravel) deposition.

Discussion of Gravel Attrition During Fluvial Transport

Coarse particles derived from deeply weathered bedrock can rapidly breakdown into finer particles by weathering in-place and by fluvial transport (Dietrich and Dunne, 1978; Madej, 1992; Hill, 1995). For example, based upon comparison between gravel percentage in soils discharged to channels to the gravel percentage in the basin sediment yield, Dietrich and Dunne (1978) estimated that approximately 80 percent of the basalt gravels input to Rock Creek, a small coastal stream in western Oregon, breakdown into finer particles during transfer through the 16.2 km² basin.

TABLE 28. MAINSTEM CHANNEL INPUTS TO BASIN SEDIMENT YIELD (as estimated from cross-section and sediment data).

Monitoring Period (water years)	Water Year	Rainfall % Normal (a)	Peakflow (cfs)	Recurrence Interval (yr)	Mainstem Sediment Production (tonnes)			Watershed Sediment Yield (tonnes)	
					Gravel	Sand	Silt and Clay	Gravel	Sand, Silt, and Clay
1980	1980	108	153	2.9	***56.5**	**31.3**	**27.4**	**23**	**149**
1981-1986	1981	66	52	I.0					
	1982	145	174	3.7					
	1983	182	210	6.0					
	1984	116	110	1.5					
	1985	68	142	2.4					
	1986	104	140	2.0					
1981-1986 total:					**80.9**	**66.8**	**85.3**	**362**	**2352**
1987-1988	1987	78	54	1.1					
	1988	80	95	1.4					
1987-1988 total:					***30.8**	**14.9**	**11.0**	**21**	**138**
Monitoring Period Annual Means:					**18.7**	**12.6**	**13.7**	**45**	**293**

Footnotes * estimated mainstem gravel production for WY 1980 and 1987-1988 are greater than estimates of watershed gravel yield- a physical impossibility. suggest that two factors likely cause mainstem gravel production to be overestimated: 1) unaccounted for sediment storage behind debris jams (only a few x-sections are located in the backwaters of debris jams); and 2) a substantial fraction of the gravels delivered to the mainstem channel breakdown into finer particles during bedload transport to the weir pond (see text p. 107-113 for further discussion).

I believe a substantial proportion of the greywacke gravels input to channels in North Fork Caspar Creek Basin rapidly breaks down into finer particles during transfer to the North Fork weir pond. This opinion is based upon: 1) the high degree of weathering and fracturing of bedrock I observed at many outcrops along inner gorge foot-slopes adjacent to mainstem North Fork Caspar Creek; and 2) the large number of pebbles and cobbles that were inadvertently broken during bulk sampling of mainstem channel sediment deposits.

To estimate gravel attrition rate in North Fork Caspar Creek basin, I compared it to Rock Creek basin where Dietrich and Dunne had previously estimated gravel attrition rate. The comparison involved: a) assigning particle abrasion coefficients to the rock types found in Rock Creek and North Fork Caspar Creek using data collected by Adams (1978) in New Zealand for similar rock types; and b) using the ratio of drainage basin areas as a surrogate for typical distances of fluvial transport in the two streams. By this approach (Table 29), I estimate that perhaps 50 percent of the gravels input to North Fork Caspar Creek break down into finer particles during transfer through the basin. As an independent cross-check, I compared percentage of gravel in soils discharged to North Fork Caspar Creek basin (27 percent) to basin sediment yield (13 percent) to also estimate that approximately 50 percent of gravels input from hillslopes breakdown into

TABLE 29. ESTIMATION OF GRAVEL ATTRITION RATE IN NORTH FORK CASPAR CREEK BASIN
(BY COMPARISON TO ROCK CREEK, WESTERN OREGON)

Drainage Basin	% Gravel (Soils)	% Gravel (sediment yield)	% Breakdown in Transit	Drainage Area (km^2)	Mainstem Channel Length (km)	Bedrock Lithology	Abrasion Coefficient (Km-1)	% Break down in Transit
Rock Creek	43	10	33+43 = **77**	16.2	11.0	Tertiary basalt	range= 0.001 to 0.005 average = 0.003	77
North Fork Caspar Creek (NFCC)	27	13	14+27 = **52**	3.8	2.4	Cretaceous-Tertiary graywacke sandstone and shale	range= 0.001 to 0.026 average = 0.008	**49** (see calculations below)

<u>NFCC Gravel Attrition Rate Bv comparison of Rock Creek and N'F Particle Abrasion Coefficients and Drainage Areas</u>

Gravel attrition in North Fork Caspar Creek = (ratio of abrasion coeffieents) x (ratio of drainage areas) x (77 percent rate for Rock Creek)

Gravel attrition in North Fork Caspar Creek = (0.008/0.003) x (3.83 km^2/16.2 km^2) x (77 percent) = **49 percent**

Notes: All Rock Creek data (except abrasion coefficient) from Dietrich and Dunne (1978).
Abrasion coefficients estimated from review of Adams (1978).

finer particles as they are transferred through the basin. The fact that the two estimates match is reassuring, and suggests that actual attrition rate is similar to the estimated value of 50 percent.

Estimating what proportion of the 50 percent attrition rate occurs in the mainstem channel by fluvial transport is more complicated. For example: a) mainstem channel length represents only a fraction of the potential fluvial transport distance in the basin (e.g., the distances from various tributary headwaters to the weir pond); and b) some gravel breakdown probably occurs by weathering in-place in stable depositional sites over long periods of time (i.e., mainstem valley fill terraces, tributary channel deposits). Even so, it is possible to estimate a maximum rate of gravel breakdown by fluvial transport in the mainstem channel by assuming that nearly all sediment production to channels comes from hillslope or active alluvial storage sites[3], and by measuring mainstem-and-tributary channel lengths to estimate minimum potential transport distance in the mainstem channel. By this approach, I estimate that mainstem channel length typically accounts for 67 percent or more of potential fluvial transport distance (Table 30), and therefore, I assume gravel attrition rate by fluvial transport in the

[3] a conservative assumption which would lead to probable overestimation of attrition rate by fluvial transport alone.

TABLE 30. COMPARISON BETWEEN MAINSTEM AND TRIBUTARY CHANNEL LENGTHS ABOVE AND BELOW TRIBUTARY D.

Stream Reach	Mainstem Length	Tributary Name	Maximum Transport Distance (a) (m)	Mainstem Channel Length Below Confluence (m)	Percentage of Potential Transport Distance in Mainstem Channel (%)
Mainstem below Tributary D		B	580	440	43.1
		C	585	560	48.9
		Unnamed	300	865	74.2
		D/E	1080	1095	50.3
subtotals:	1095	...	2545	2960	53.8
Mainstem above Tributary D		G	460	1440	75.8
		H	660	1850	73.7
		1	455	1905	80.7
		Unnamed	210	2350	91.8
subtotals:	1355	...	1785	7545	80.9
Mainstem Channel above and below D	2400	...	4330	10505	70.8

FOOTNOTE:
(a) assuming gravel source is located at the headwaters of the most distant tributary within the named sub-basin.

mainstem channel is 33 percent or less (50 %, attrition rate for the basin multiplied by 0.67 = 33 percent).

Unaccounted for Increase in Sediment Storage Behind LWD Jams

Review of field notes taken during establishment and survey of channel cross-sections, reveals that when cross-sections were established in 1979, none were affected by debris jam backwaters. By the end of 1980, only a few cross-sections were affected by debris jam backwaters, as was the case in 1987 and 1988.

In Table 7, the time of formation and recent sediment storage changes (1985-1987) for large debris jams (e.g., sediment storage ≥ 25 m^3) are noted. This data can be used to estimate sediment storage changes in debris jams that occurred in WY 1980 through 1988 because: 1) 1980 cross-section survey notes describe the presence or absence of LWD jams; and 2) based on field observations and mapping in the summers of 1987 and 1988, I conclude that little or no increase in sediment storage occurred in debris jams backwaters during the preceding wet seasons. I compute that, between WY 1980 and 1986, sediment storage in large debris jams increased by about 87 m^3. 75 percent of sediment in debris jams is gravel sized (Table 2) and large debris jams accounted for 75% of total debris jam sediment storage as of 1987 (Table 4). Therefore, I estimate that average annual increase in gravel storage behind debris jams during

WY 1980-1986 was approximately 23 tonnes per year (e.g., 87 m^3 x 1.82 tonnes/m^3 x 0.75 [gravel fraction] / 0.75 [fraction of total debris jam storage] / 7 years). Unaccounted for increases in debris jams storage should be less than this value.

Reconciliation of the Sediment Budget

Accounting for maximum gravel breakdown rate, and possible undercounting of LWD jam filling brings estimated mainstem gravel contributions, in WY 1980 and 1987-1988, into balance with estimated gravel yield from the basin (Table 31). Revised estimates for sand and fine sediment inputs from the mainstem channel to basin yield are presented in Table 32.

Important sediment routing relationships are revealed in Tables 25, 31, and 32. In average and dry water years (e.g., WY 1980, 1987-1988), mainstem channel gravel sources apparently constitute a large fraction of the gravel yield from the basin (Table 31). Conversely, in wet periods, like WY 1981-1986, mainstem channel sources account for only a small fraction of gravel yield. This occurs because peak flows are moderate to short in duration in most dry and average water years (Table 27), and hence, most basin gravel yield comes from nearby sources: the mainstem channel. In wet years, storm durations, soil saturation, peak flows, and duration of bedload transport

TABLE 31. CONTRIBUTION OF THE MAINSTEM CHANNEL TO GRAVEL YIELD FROM THE BASIN

Contributions/Processes Affecting Transfer Through the Channel	water year 1980 (tonnes per year)	water years 1981-1986 (tonnes per year)	water years 1987-1988 (tonnes per year)
Mainstem Sediment Production:			
Valley-Fill Bank Erosion	35.8	35.3	3.3
Hillslope Bank Erosion	9.3	5.8	3.4
TOTAL:	45.1	41.1	6.7
Active Channel Storage Changes (a):	15.5	-27.6	8.7
Mainstem Channel Sediment Input to Basin Yield (b)	56.6	13.5	15.4
Maximum Attrition by Fluvial Transport:	-18.7	-4.5	-5.1
Unaccounted for LWD Storage Increases (c):	-(0.0 to 23.0)	-(0.0 to 23.0)	-(0.0)
Estimated Delivery from Mainstem Channel (d):	14.9 to 23.0	0.0 to 13.5	10.3 to 10.5
Basin Yield:	23.0	60.3	10.5
Estimated Delivery from Mainstem (% of basin yield):	66%100%	0%22%	98%100%
Best estimates (in tonnes per year) (e):	19	6.8	10.4

NOTES: Positive numbers reflect net contributions to basin yield; negative numbers reflect increases in channel storage. breakdown of gravel by fluvial transport. and unaccounted for increases in channel storage (e.g., factors which may attenuate gravel delivery from the mainstem channel).

FOOTNOTES: (a) as estimated from cross-section and sediment sampling data
(b) mainstem sediment production plus change in active channel storage.
(c) estimated range based upon analysis of times of formation of large debris jams and average annual increases in sediment storage in WY 1980-1986. On the basis of detailed geomorphic mapping (1987), field obsevations. and cross-section surveys (1988). 1 infer no increases in storage at LWD jams in 1987-1988.
(d) Mainstem channel sediment input (from cross-section and sediment data) minus attrition and unaccounted for increases in LWD jam storage. Maximum values are bounded by estimated total gravel yield from the basin.
(e) mid-points of inferred ranges.

TABLE 32. MAINSTEM CHANNEL CONTRIBUTION TO SAND AND FINE SEDIMENT YIELD FROM THE BASIN

	WY 1980			**WY 1981-1986**			**WY 1987-1988**		
Estimated on the basis of:	Mainstem Contribution Sand (tonnes)	Silt-Clay (tonnes)	Basin Yield (sand, silt and clay) (tonnes)	Mainstem Contribution Sand (tonnes)	Silt-Clay (tonnes)	Basin Yield (sand, silt and clay) (tonnes)	Mainstem Contribution Sand (tonnes)	Silt-Clay (tonnes)	Basin field (sand, silt and clay) (tonnes)
Cross-section and sediment data	31.2	27.4	149	66.9	85.2	2352	14.9	10.9	138
maximum potential attrition:	18.7			26.7			10.2		
accounting for attrition (a):	(31.2 to 49.9)			(66.8 to 93.5)			(14.9 to 25.1)		
unaccounted for LWD Jam filling:	7.6			45.3			0 (d)		
accounting for attrition and LWD Jam filling (b).	(23.6-49.9)			(21.5 l0 93.5)			(14.9 to 25.1)		
Best Estimates (c).	**36.8**	**27.4**	**149**	**57.5**	**85.3**	**2352**	**20.0**	**10.9**	**138**

NOTES: values in parentheses represent intimated range.

FOOTNOTES: (a) assuming maximum gravel breakdown rate: all of this becomes sand-sized particles.

(b) as sand constitutes approximately 25% of jam storage by volume. maximum unaccounted for sand storage =
87 m3 (filling of large jams in WY 1980-1986) x 1.82 kg/m3 (bulk density of channel sediment) x 25% by volume (% sand in debris jams)
÷0.75 (fraction of total LWD jam storage in large jams).

(c) mid-point of estimated range.

(d) Based upon detailed geomorphic mapping (1987), field obsevations, and cross-section surveys, I infer no increase in LWD jam storage in 1987-1988.

are much longer and more sustained. Therefore, gravel may be delivered from a variety of nearby and more distant sources located throughout the basin. The same basic relationship also holds for sand and fine sediment contributions from the mainstem channel to basin yield (Table 32). In WY 1980 and 1987-1988, mainstem channel sources accounted for about 20 and 40 percent, respectively, of sand plus fine sediment yield, but only 6 percent in WY 1981-1986 (Table 32).

If not for substantial increases in channel storage, primarily in reach A. coarse sediment yield would have been much higher (Table 26). Much of the increase in sediment storage in reach A apparently occurred in response to routing of landslide sediment from reach L through F and into A. Sediment storage trends in reaches A, F, and L in WY 1980-1988 illustrate this process: storage in bars and debris jams in reaches F and L declined by about 20 percent. however, it increased by about 50 percent in reach A (Figure 19).

Storage trend data and field observations of debris jam storage capacity reveal that North Fork Caspar creek has little remaining sediment storage capacity. Given a similar hydrologic period to WY 1980-1988, 1 would expect gravel yield to rise by an amount roughly equivalent to the increase in channel storage during WY 1980-1988: or about 15 tonnes per year.

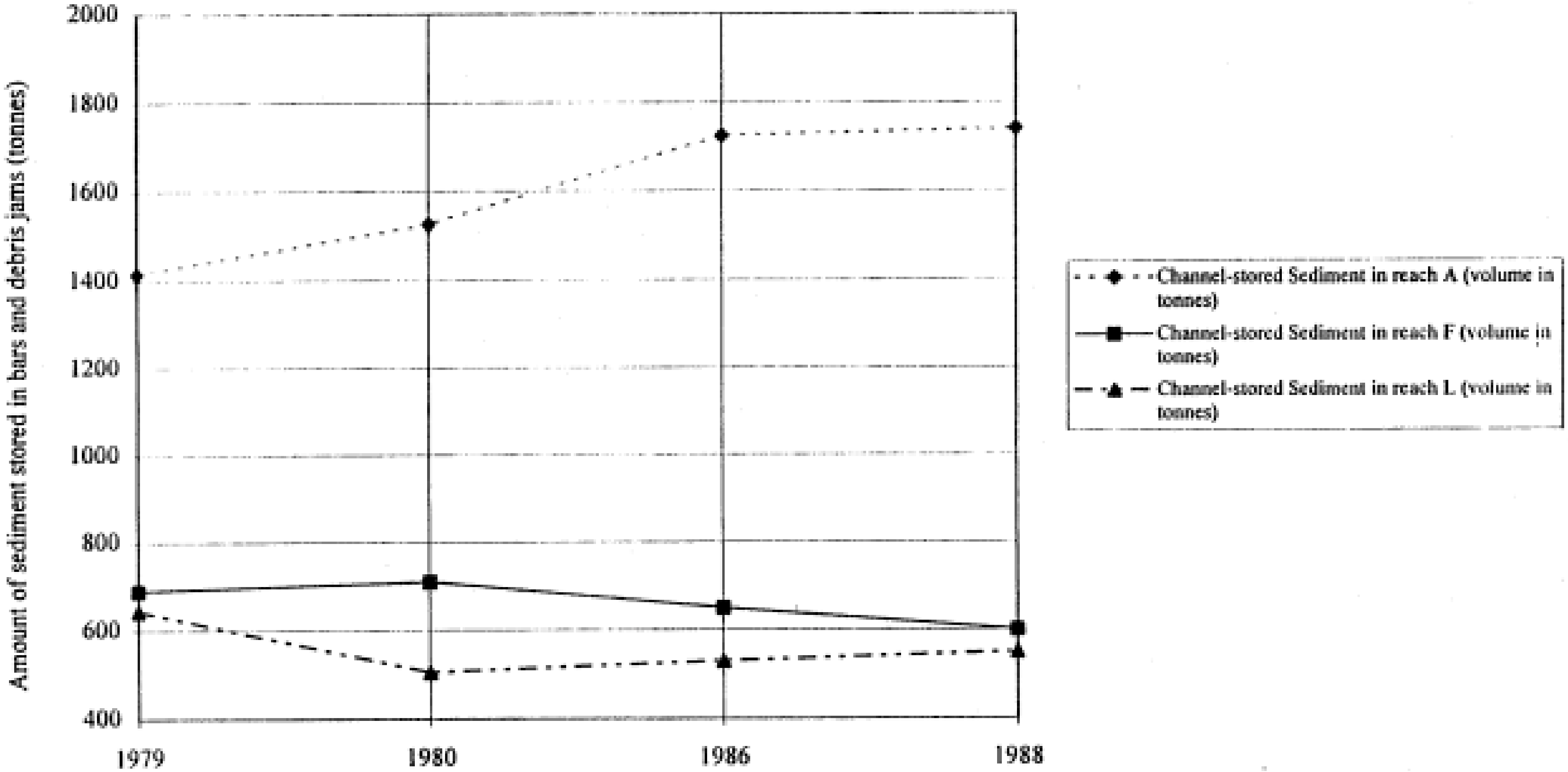

FIGURE 19. Active channel sediment storage trends in reaches A, F, and L during WY 1980-1988

3.6 SUMMARY AND CONCLUSIONS

1) Weir pond sedimentation data together with suspended-load measurements provide a reasonable basis for estimating sediment yield from North Fork Caspar Creek basin. Using these data, I estimate that average annual sediment yield during WY 1980-1988, was approximately 69 tonnes per km^2 per year, 9 tonnes of which was bedload (Table 20). Average annual yield in WY 1963-1976 was much higher: 262 tonnes per km^2 per year. Large floods in WY 1966 and 1974 (both had R.I. = 27 yr.) and discharge of a large landslide (3300 m^3) to the mainstem channel in March of 1974 account for the differences.

2) Sediment yields from North Fork Caspar Creek are similar to estimates for other basins in competent Franciscan terrane where a substantial portion of the basin has been previously logged (Janda. 1972, Kelsey, 1980, Madej et al. 1986). Comparison to limited published data on sediment yield from streams in old-growth redwood forest underlain by competent Franciscan terrane suggests that historical logging of Caspar Creek may have caused persistent increase in basin sediment yield. Additional data are needed to draw definitive conclusions.

3) The vast majority of the changes in channel sediment storage in WY 1980-1988, occurred at or near LWD jams, recent slidescars, and tributary junctions. Elsewhere, the streambed is well armoured, and little change in storage occurred.

4) Although North Fork Caspar Creek is a small headwaters basin, breakdown of gravel is rapid and intense by weathering in long-term, storage sites and by fluvial transport. I compared percentage of gravel in soils discharged to channels (27 percent) to basin sediment yield (13 percent) to estimate that approximately 50 percent of gravels input from hillslopes break down into finer particles as they are transferred through the basin. A fractional proportion of this rate occurs through fluvial transport along the mainstem channel.

5) The effect of LWD on sediment routing and yield was fairly neutral during the monitoring period. Although the amount of sediment stored in debris jams increased by about 160 tonnes in WY 1980-1988, bank erosion caused by LWD was about 200 to 300 tonnes. Examination of debris jams reveals little remaining storage capacity. Therefore, in the near future, coarse sediment will be more rapidly transferred through the mainstem channel. Most debris jams fill rapidly, and once filled, collapse during common flow events (R.I. < 5 yrs.).

Therefore, depending upon antecedent jam storage and the character of individual water years, jams act as short-term sinks or sources which can substantially alter coarse sediment yield from the basin.

7) No overbank deposition or deposition of new valley fills was noted during water years 1980-1988 (peak flows had R.I. ≅ 6 yrs.). Review of flood frequency and stage data in the vicinity of station A suggests that most valley fills are not over-topped during common floods (R.I. ≥ 50 yrs.). Old-growth stumps in growth position on many of the fills attest to the long-term sediment storage in the fills. Lack of soils on fills indicates, however, that isolation from flooding and overbank deposition is a fairly recent phenomena. On the basis of comparison of sediment production from valley-fill bank erosion (309 tonnes) to coarse sediment yield (406 tonnes), valley-fill bank erosion appears to be a source of coarse sediment to the channel. Prior to isolation of terraces, input of coarse sediment to the valley fills would have been in balance with output. This change apparently has important consequences for valley fill storage trends and basin sediment yield.

CHAPTER 4: PERSISTENCE OF HISTORICAL LOGGING IMPACTS

4.1 EFFECTS OF LWD AND HISTORICAL LOGGING ON THE SEDIMENT BUDGET

On the basis of comparison of sediment yields for North Fork Caspar Creek to limited data for similar streams in old-growth forest, it appears that logging may have caused a persistent increase in sediment yield.

The net effect of LWD on the sediment budget for North Fork Caspar Creek apparently is fairly neutral. At present, most LWD jams in North Fork Caspar Creek are rapidly filled within a few years of formation (Table 7). Many jams collapse or partially collapse during common floods (R.I. < 5 yrs.). As of 1987, nearly all of the LWD jams in North Fork Caspar Creek were nearly full or at capacity, affording little prospect for future attenuation of large sediment inflows.

This situation contrasts greatly with the substantial sediment storage capacity provided by LWD jams in streams draining old-growth redwood forests (Keller and Tally, 1978). There, LWD provides long-term, large-volume sediment storage sites (Keller and Swanson, 1979), and it exerts a significant influence on aquatic habitat diversity. Based upon comparison of channel form and LWD loading and stability in North Fork Caspar Creek to similar streams in old-growth redwood forests (Keller et al., 1981), it appears that LWD loading and stability is substantially lower in North Fork Caspar Creek. Historical logging activities in Caspar Creek basin may be the cause for these differences. For example, historical logging activities included: a) log drives; b) splash dam releases; and c) removal of all channel obstructions including LWD (Brown, 1936) to prepare the channel for the log drives.

Absence of flood-plains and presence of prominent valley fill terraces along North Fork Caspar Creek may also be a result of historical logging. If so, valley fills have been converted from large-volume, long-term sediment sinks (floodplains) to substantial coarse sediment production sources (terraces) suggesting a major change in valley sediment storage trends and the sediment budget for the basin.

To evaluate whether historical logging has caused persistent changes in channel form, LWD loading and stability, I analyzed the following data: 1) research regarding the effect of LWD on channel form and function in streams draining second- and old-growth redwood forest; 2) history of nineteenth century logging activities at Caspar Creek; and 3) field evidence for historical disturbance or removal of LWD from North Fork Caspar

Creek. Based upon analysis of these data, I discuss probable channel response to nineteenth century logging activities.

4.2 COMPARISON OF NORTH FORK CASPAR CREEK TO SIMILAR STREAMS IN OLD-GROWTH COAST REDWOOD FOREST

The following paragraph summarizes the findings of Keller and Tally (1981) regarding the role of LWD in steep, headwaters, streams draining old-growth redwood forests. They found that LWD provides:

a) a stepped profile where in a significant proportion of the stream's total energy is dissipated locally at plunge pools below debris dams,

b) stable channel roughness elements that provide large-volume, long-term sediment storage sites (often stable for hundreds of years) effectively buffering the channel from infrequent large-magnitude sediment inflows, and

c) stable structure that creates a diverse assemblage of channel morphologies and flow conditions.

Stable and diverse channel form creates excellent fish habitat. Interrelated physical factors (stream order, discharge, valley width, channel type, channel slope), large woody debris input processes, and size of debris elements interact to control large woody debris loading, distribution, and stability over time (Keller, Mac Donald, and Tally, 1981). The influence of LWD on channel form-process is directly related to its loading, distribution, and stability over time.

Research by Tally (1980) demonstrates that much of the variability in debris loading along a particular stream draining an old-growth redwood forest is related to frequency of "large diameter redwood trees" (Table 33). When physical input factors are uniform, debris loading is primarily a function of tree frequency, and therefore, physically similar channels should have comparable debris loading given similar forest cover.

Prior to nineteenth century logging, tree frequency on North Fork Caspar Creek is likely to have been within the range for steep mountain streams in old-growth (e.g., those without extensive floodplains) that were surveyed by Tally (1980). Tree frequency along these streams varies from 26 to 68 per hectare. Keller, MacDonald. and Tally (1981) compared several streams in second- and old-growth redwood basins to assess how the influence of LWD on channel form and process may be altered in second-

TABLE 33. LWD LOADING IN STREAMS DRAINING OLD-GROWTH REDWOOD

Stream	Reach	Debris Loading (kg/m³)	Number of Large redwoods near the channel (a)	Flood Plain
Hayes Creek		170	68	none
Little Lost Man Creek	Upper	141	52	none
	Middle	268	40	none
	Lower	49	26	none
Prarie Creek	Hope Creek	218	80	minor
	Little Creek	12	25	yes
	Forked Creek	13	21	yes
	Zig Zag No. 2	22	25	yes
	Natural Tunnel	106	41	minor
	Brown Creek	85	75	none
	Campground	20	32	yes

Notes:

(a) number of large redwood trees per hectare within 50 meters of the stream channel

R^2 for debris loading vs. large redwood frequency = 0.88

Source: Tally (1980).

growth basins (Table 34). North Fork Caspar Creek was one of the second-growth basins studied. Keller et al. (1981) estimated debris loading's of 21 to 24 kg/m in North Fork Caspar Creek. Of the old-growth streams studied by Keller, upper Little Lost Man Creek is the most similar to North Fork Caspar Creek (Table 35). Both are steep, second-order, gravel-bedded streams with narrow valleys, similar drainage area, channel width, and slope. Therefore physical factors effecting LWD input and loading should be similar. Large redwood tree frequency in Little Lost Man Creek is 26-to-52 per hectare and debris loading is 49-to-268 kg/m (Table 33) or two-to-seven times more than in North Fork Caspar Creek. Therefore it appears that debris loading, and consequently the influence of LWD on channel form and process, was much greater in North Fork Caspar Creek prior to logging. Much higher debris loading in Little Lost Man Creek provides significantly greater LWD-related sediment storage capacity (Table 36). LWD jams in Little Lost Man Creek store about five times as much sediment, and have approximately twenty times as much unfilled storage capacity as in North Fork Caspar Creek. LWD-related storage capacity at Little Lost Man Creek provides an important buffer system for the channel allowing infrequent large-magnitude sediment inputs to be stored in jams and released slowly over time. In contrast, LWD-related storage capacity in North Fork Caspar Creek is insignificant and hence, infrequent large sediment inputs are not effectively buffered (Table 36).

TABLE 34. CHANNEL ATTRIBUTES FOR STREAMS IN SECOND- AND OLD-GROWTH REDWOOD FORESTS (source: Keller, MacDonald, and Tally, 1981).

	Second-growth			Old-growth								
						PRAIRIE CREEK:						
Study Reach:	North Fork Caspar Creek upper/lower	Lost Man Creek	Larry Damm Creek	Hayes Creek	Little Lost Man Creek U pper/Lower	Hope Creek reach	Little Creek Reach	Forked Creek Reach	Zig Zag No. 2 Reach	Natural Tunnel Reach	Brown Creek Reach	Campground Reach
Basin area (km²):	1.6/3.9	1.1	3.7	1.5	3.5/9.1	0.7	3.5	6.6	8.2	11.2	16.7	27.2
stream order:	2/2	2	3	2	2/2	2	2	2	2	2	3	4
slope:	.016/.013	.048	.014	.12	.033/.048	.020	.014	.012	.009	.010	.010	.005
Debris loading (kg/m²):	21/24	105	76	170	142/49	218	12.3	13.1	21.7	106	84.8	19.6
pool to pool spacing (a).	3.5/3.8	4.1	2.2	2.4	1.9/1.8	6.2	4.7	2.6	6.6	2.7	6.0	4.0
% of area in pools:	24/36	33	27	12	22/18	49	34	46	36	41	26	25
% of area in riffles:	30/30	25	14	26	15/21	21	-16	49	20	15	18	25
% in debris-stored sediment:	44/34	43	59	40	39/39	30	18	30	15	21	29	13
% area in undercut banks:	2/1	4	2	4	3/1	1	4	3	4	1	< 1	1
% pool uwrphology influenced by debris:	82/43	79	59	83	100/90	86	71	87	50	80	67	50
Debris controlled drop in elevation (%):	57/37	69	17	38	59/30	43	27	34	8	< 1	18	< 1

NOTES:

Total percentages in stream enivomments may be less than or greater than 100% due to overlaps between units (such as pools which contain debris-stored sediment)

FOOTNOTES:

(a) expressed in units of channel width.

TABLE 35. CHANNEL ATTRIBUTES OF NORTH FORK CASPAR AND LITTLE LOST MAN CREEKS

Stream	Forest Cover	Basin Area (km²)	Slope (m/m)	Channel Sinuousity (m/m)	Channel Width (a) (m)	Channel Boundaries
Upper Little Lost Man	old-growth	3.5	0.03	1.1	6.4	hillslopes or narrow valley flat
North Fork Caspar	second-growth	3.8	0.02	1.1	4.8	narrow valley flat and/or hillslopes

Footnotes:

(a) mean channel width = channel area per centerline channel length

Data for Little Lost Man Creek from Keller and Tally (1979).

TABLE 36. LWD-RELATED SEDIMENT STORAGE
IN LITTLE LOST MAN AND NORTH FORK CASPAR CREEKS

Stream	Forest Cover	Debris Loading (kg/m^3)	LWD Sediment Storage (t/km^2)	Available Storage (a) (t/km^2)
Upper Little Lost Man	old-growth	141	1795 (b)	1010 (b)
North Fork Caspar	second-growth	24	340 (c)	< 50 (c)

Footnotes: LWD, large woody debris.

Notes: (a) remaining sediment storage capacity.

(b) on the basis of data in Keller et al. (1981), and assuming: sediment storage per unit drainage area is similar in upper and lower Little Lost Man Creek; and bulk density of sediment in storage is approximately l.8 tonnes per m3.

(c) North Fork Caspar Creek sediment storage data on the basis of data collected for this study in the summer of 1987.

All Little Lost Man Creek data, and debris loading data for North Fork Caspar Creek are from Keller et al. (1981).

4.3 HISTORY OF NINETEENTH CENTURY LOGGING AT CASPAR CREEK

Caspar Creek was first logged in 1860 and most of the watershed was clear-cut and burned between 1864 and the mid-1890's. Caspar Lumber Company records indicate that, on average, redwoods logged from Caspar Creek watershed were six to eight feet in diameter. Transportation of logs to the company mill located on the coast involved construction of a logging splash dam near the headwaters of the North Fork Caspar Creek. The water stored upstream of the dam was released during large storms with the goal of increasing streamflow enough to sustain the log drives. During each log drive thousands of logs were transported down the creek (see Appendix I). In tributaries of Big River, located a few kilometers south of Caspar Creek, log drives occurred an average of two-times per year (Francis Jackson, personal communication). Assuming a similar frequency of log drives in Caspar Creek over the historical logging era, I estimate that approximately sixty log drives occurred on North Fork Caspar Creek. Also, before log drives could be conducted a stream channel had to be "improved". Channel improvement involved "removal or blasting of boulders, large rocks, leaning trees, sunken logs or obstructions of any kind" (Brown, 1936).

4.4 FIELD EVIDENCE OF CHANNEL IMPROVEMENT AND LOG DRIVES

Evidence of channel preparation for log drives along the mainstem North Fork Caspar Creek can be found by examining in-place old-growth stumps on valley fills. The old-growth redwood stumps that I located are commonly obscured by mature stump sprouts or by shrubs growing up through the stump (Figure 20). I believe it is likely, therefore, that old-growth stumps are present on other terrace surfaces where they have not been recognized. As valley width is narrow (3 to 20 meters) along most of North Fork Caspar Creek, stumps were cut below the root swell of the trees, flush with the ground surface to avoid snagging of floated logs during drives. All other old-growth stumps in the basin (e.g., those on terrace margins and hillslopes) were cut well above the root swell, many feet above ground surface (Figure 21) because workers were paid by the small diameter of the trees they cut (Francis Jackson, personal communication).

Direct evidence of removal of LWD elements from the channel of North Fork Caspar Creek is difficult to find. Characteristics of LWD within the active channel, however, suggest logs were removed or blasted. Almost without exception, LWD in the channel

FIGURE 20. Old-growth stumps on valley tills adjacent to the channel: stamps were cut close to the ground surface; they are now obscured by understory vegetation and/or nursed second-growth trees.

FIGURE 21. Old-growth stump on inner gorge slope:
stump was cut high above the root-swell of the trunk.

today is ≤ 0.5 meters diameter; approximately the same diameter as the largest second-growth trees within the basin. In at least one location, an old-growth sized LWD trunk is partially buried within the right bank of a valley fill terrace just downstream of Tributary H (Figure 22). This trunk is cut obliquely, and flush with the ground surface of the valley fill deposit. Prior to cutting it probably extended across the valley width, obstructed streamflow, and possibly was part of a LWD dam that would have hindered efforts to float logs downstream. Other smaller old-growth logs are similarly oriented and partially buried within the right bank terrace a few meters upstream (Figure 22).

4.5 CHANNEL RESPONSE TO NINETEENTH CENTURY LOGGING ACTIVITIES

Removal of large roughness elements (including LWD jams), increased peak flows associated with splash dam releases, and abrasion caused by repeated transport of thousands of logs, would encourage streambed degradation.

A large fraction of the sediment, stored in debris jam backwaters would probably have been liberated because controls on deposition (large roughness elements) were removed

(Above): a trunk buried in terrace shown below. Note that it is cut obliquely and flush with the ground surface. Prior to cutting this trunk may have extended across the width of the valley.

FIGURE 22. Old-growth trunks which may have formed a debris jam prior to cutting.

during channel preparation. Considering the average diameters of trees logged in Caspar Creek (6 to 8 feet), where jams extended across the width of the active channel, it may have degraded substantially. Most of the sediment stored in valley fills, however, probably was not eroded because of the resistance to erosion afforded by large and extensive root networks of the old-growth trees growing on the fills.

Prior to the log drives and channel improvement, I believe the mainstem channel, below the splash dam, resembled the present-day character of the reach located upstream of the splash dam backwater. In this reach the channel is only slightly entrenched (typically channel banks are < 2 feet high), and it has a much higher width-to-depth ratio than below the splash dam. Its planform, typically, is anastomosing with a well-defined main channel and auxiliary high-flow channels. I have two reasons for my opinion:

1) under present-day conditions, the largest second-growth trunks input to the channel, in the reach upstream of the splash dam, do not appear to be mobilized by frequently occurring peak flows. Therefore, debris loading apparently is higher above the splash dam backwater, and jams are more frequent. Hence this reach may resemble an appropriately scaled analog to the pre-logging channel form below the splash dam.

2) Channel morphology in the above splash-dam reach resembles Little Lost Man Creek, the old-growth channel which I believe is most similar to North Fork Caspar Creek.

Lack of soils on the valley fills suggests they were frequently overtopped, at least as recently as several hundred years ago (e.g., the time it would take for a soil A horizon to form). The fact that old-growth trees on the valley fills were cut flush with the ground surface suggests that the persons preparing the channel for log drives believed this was necessary to avoid snagging cut logs during drives.

The channel has not recovered its previous morphology because jams in the channel are now less stable in time, stepping is less pronounced with smaller diameter trunks, and the resistance to bank erosion afforded by second-growth trees on the valley tills limits lateral migration-rate. This causes the channel to remain entrenched, and to have a narrower width-to-depth ratio (typically w/d ratio in the mainstem channel is 10 to 11) than the reach above the splash dam. It is unlikely that the channel will recover its former morphology, however, until the former relationship between LWD caliber and flow magnitude is re-established.

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APPENDIX I: Historical Documentation of Logging in the Caspar Creek Basin

Caspar, California was named after its first European settler, Siegfried Caspar, a trapper who lived and worked near the mouth of Caspar Creek prior to 1860. In 1860 William H. Kelly and William T.Rundle founded the Caspar Logging Company. That year they purchased 5000 acres of forested terrain in the Caspar Creek basin, and built a saw mill at the mouth of Caspar Creek. Kelly and Rundle's original mill had a capacity of 25,000 board feet per day. After logs were transported to the mill and cut into boards, they were ferried by barge from a mill pond to schooners anchored a short distance offshore. A few years after logging began, barges were replaced by an incline and chute system, as sedimentation of the mill pond precluded further barge transport. The incline and chute system delivered boards to the top of the "bluffs" (marine terraces), where they were lowered by cableways to the schooners. In 1861, Jacob Green Jackson was taken on as a third partner in the Caspar Lumber Company. By 1864, Jackson had taken over the company. Kelly and Rundle were then forced out by Jackson, when he claimed their interests in the company as payment on debts owed to him. Under Jackson's ownership the Caspar Lumber Company grew rapidly, and eventually became one of the most successful logging companies on the Mendocino coast.

Soon after obtaining sole ownership in 1864, Jackson hired engineers to build three crib dams on Caspar Creek. The crib dams were constructed to provide additional stream discharge for transporting logs to the mill by during log drives. With the dams constructed, logging operations were expanded high into the headwaters of Caspar Creek Basin.

Remnants of three crib dams on Caspar Creek have been located by Francis Jackson, a longtime resident of the Mendocino area and expert on its logging history. Typically logging dams were constructed in the uppermost reaches of a stream to maximize the length of stream channel below the release point of the water. Two dam sites that were located by Francis Jackson, are at the headwaters of the South and North Fork of Caspar Creek. The third dam was built on the mainstem channel a few miles upstream from the ocean. A picture of a crib dam on South Fork Caspar Creek was taken in 1868 and it is reprinted in *Mallets On The Mendocino Coast* (Wurm, 1986). The dams on Caspar Creek, like most on the Mendocino coast at the time, were constructed with a flume**,** a spillway built through the center of the dam, and a triggering mechanism that allowed the dam operator to open its gate. The upstream and downstream face of the dam were constructed with the cut logs cribbed together log cabin style. The core of the dam between the two faces was composed of rock and soil.

The North Fork and South Fork dams provided the necessary additional streamflow that allowed logs to be floated down each fork and a considerable distance along the mainstem Caspar Creek below their junction. Along the mainstem Caspar Creek the stream gradient becomes gentle, and therefore it was necessary to build a third splash dam where the mainstem valley opens to become much wider and is bound by broad floodplains and terraces. Moving logs through this dam was called "sluicing", and was accomplished by opening the gate on the flume, allowing water level to drop to a safe level, and then having men walk on "boom sticks" in the pond to guide logs through the flume. This final pulse of streamflow was necessary to successfully transport logs to reach the mill.

Contemporaneous with dam construction, skid roads and roll aways were excavated in the woods. Skid roads, or corduroy roads as they were often called, were built as straight and level as possible. Tan oak and other trees of low economic value were cut to provide wood for the skids used on corduroy roads. Corduroy roads were straight because oxen, and later bulls, were used to transport cut logs along the roads. Corduroy roads were constructed by placing and half-burying heavily greased skids (logs) in the ground at short, even intervals equal to step length of the oxen. They were built in this fashion to prevent oxen from catching their hooves on the skids. Logs were transported by a team of animals as a train with single log sections chained together along a line, and delivered to roll away platforms. Log trains were made easier to move by applying a ladle full of water to a skid just before a log passed.

To facilitate the skidding, logs were felled and bucked into 12 to 16 foot lengths, and the bark was peeled off. Bark and large amounts of waste from the tops of the trees, and breakage presented a problem in transporting the logs downslope to the skid roads. The "solution" to this problem was to burn the area as soon as it was dry enough to carry fire. Burning was usually done in late summer or early fall (Sullenberger, 1980). The use of fire was especially suited for redwood trees, because their heartwood is resistant to burning. Continual dampness generally stopped fires from burning beyond slash, bark and dead wood on bucked logs, and the organic horizon of the soil. Usually, a year passed between skidding and the time trees were cut.

Logs were transported along skid roads to roll aways. Roll aways, as the name suggests, were depots where log trains were unloaded and transferred into the stream channel. Jack screws (mechanically analogous to car jacks) raised unloaded logs, and popped them into the creek. Log tiers were then carefully or sometimes haphazardly constructed as logs were popped into the creek. Tiers usually were four to five logs high with logs oriented parallel to the stream channel. Considering the six to eight foot average diameter of logs (Caspar Lumber Company records) the tops of log tiers were often 30 to 40 feet above the channel bed.

Log drives, however, were uncertain propositions where too much water, an insufficient boom at the mill (intended to keep logs from going out to sea), too little water, or channel obstructions often limited the success of the drives. Articles in *The Mendocino Beacon* refer to many instances where the Caspar mill was forced to shut down after logs had washed out to sea, formed log jams along the creek, or were not deliverable because of low winter rainfall (which meant insufficient water behind the dams and along the creek to transport the logs). Quotations from articles in *The Mendocino Beacon* document the size, and relative success of some Caspar Creek log drives:

> 3 September 1881
>
> "Hargraves Camp (on Caspar Creek) over 3,000 logs already cut this summer"
>
> 10 March 1883
>
> " 30 to 32,000 cut logs on Caspar Creek waiting for a freshet "
>
> 15 March 1884
>
> " A one and one-half mile log jam (on Caspar Creek) will take an uncommon freshet to move them"
>
> 28 March 1885
>
> " Temporary dam succeeded in building sufficient head to bring 6,000 logs downstream to the mill" (from a large log jam on Caspar Creek just downstream of the dam)

A log drive was considered successful if half or more of the logs stored within the stream reached the mill. From reviewing Union Lumber Company files of the log drives on the Big River system near Mendocino, Francis Jackson has computed an average of two log drives per winter for the Big River. Log drives required a "freshet" as well as a full crib dam reservoir. A "freshet" is loosely defined as a storm capable of raising the water level of the stream by about two feet (the stage necessary to float a four foot diameter log). During freshets local stream levels rapidly rise and fall. The crib dam operator had the diffcult task of deciding whether or not to open the dam during a freshet.

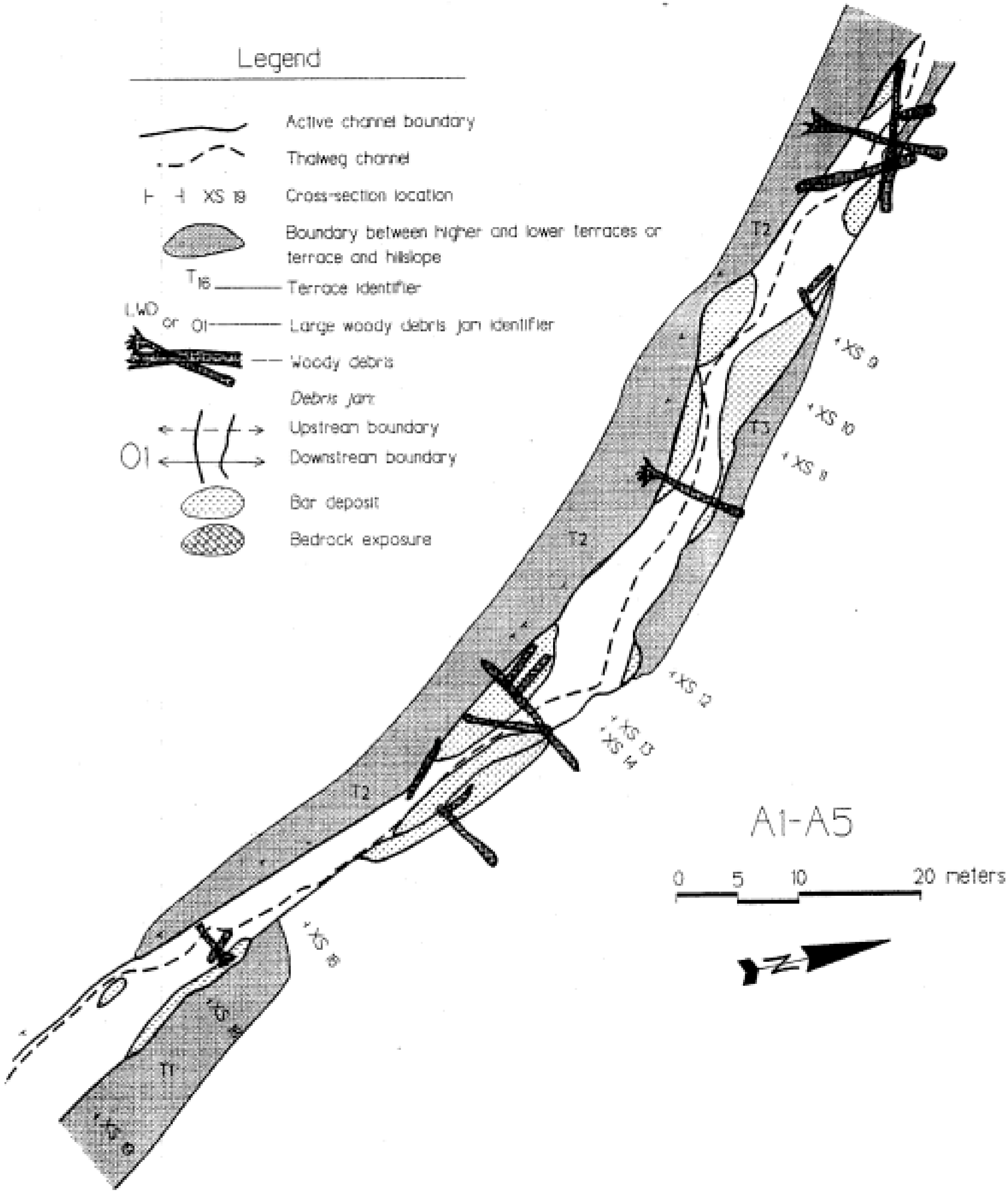
Given inherent uncertainties of transporting logs by water, a more dependable alternative was sought and developed in 1877: railroad transport. Jacob Green Jackson was an excellent businessman who always planned for the future and early in the 1860's, he began purchasing additional land north of Caspar Creek. When the Jug Handle Creek Basin was purchased, a standard gauge tramway was constructed from the Caspar Creek mill pond across the marine terrace between Caspar and Jug Handle Creek and down into the Jug Handle Creek gorge. Animal power was used to transport a train of three to four cars of logs, six times per day (how many logs could be transported per car was not noted). This method did not match log drives in volume of timber delivered. It did, however, provide a large enough alternative supply of timber to keep the mill open during dry winters.

In 1877, the tramway to Jug Handle Creek became a full fledged railroad. *The Mendocino Beacon* mentions the first run of a locomotive on the line as December 15, 1877. Also in 1877, Jackson continued expanding northward with the purchase of a sizable portion of the Hare Creek basin. The land at Hare Creek was needed because Jug Handle Creek was scheduled to be logged out by 1885, and Caspar Creek by the early 1890's.

Completion of logging at Caspar Creek may have been interrupted, however. The North Fork Caspar Creek crib dam appears to have failed during the winter of 1884-1885. The March 28, 1885 addition of *The Mendocino Beacon* mentions a new dam. It notes: "Temporary dam (on Caspar Creek) has succeeded in building sufficient head to bring 6000 logs downstream to the mill" (from a log jam just downstream of the dam). The November 11, 1885 edition states "500 logs driven with new dam just built this summer." Neither of these articles mentions the fork where the new dam was constructed, but at that time, the South Fork Caspar Creek was referred to as Whites Creek. The articles also do not actually describe a dam failure.

In recent years, Francis Jackson has located crib dams near the headwaters of the South and North Forks of Caspar Creek, and on the mainstem of Caspar Creek. At the North Fork dam site there are remnants of two dams are constructed very closely together. A failure can only be considered as well reasoned speculation, but it offers a satisfying explanation for the construction of an entirely new dam approximately 30 feet downstream of a larger dam near the headwaters of North Fork Caspar Creek.

Logging was completed at Caspar Creek in 1904. Logging over most of the watershed had been completed by the late 1890's. An incline spur was constructed in 1900 to deliver timber from the last remaining uncut tributary on the North Fork. The incline tramway ran uphill from the Hare Creek railroad line to the ridge dividing Hare Creek and the North Fork Caspar Creek, down into the North Fork gorge and back into tributary D-E. Remnants of the tramway are well preserved today along a portion of the stream bed of the tributary E, and along the slope of the North Fork Gorge north toward Hare Creek. The tramway, crib dams, corduroy roads, old-growth stumps, scattered old-growth trees, and other historical artifacts are common throughout the North Fork Caspar Creek basin. They provide the careful observer a rich source of materials from which to reconstruct the history of logging at Caspar Creek.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Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or O1
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
O1
Downstream boundary
Bar deposit
Bedrock exposure
T2
T3
T2
T2
T1
XS 9
XS 10
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XS 12
XS 13
XS 14
XS 15
XS 16
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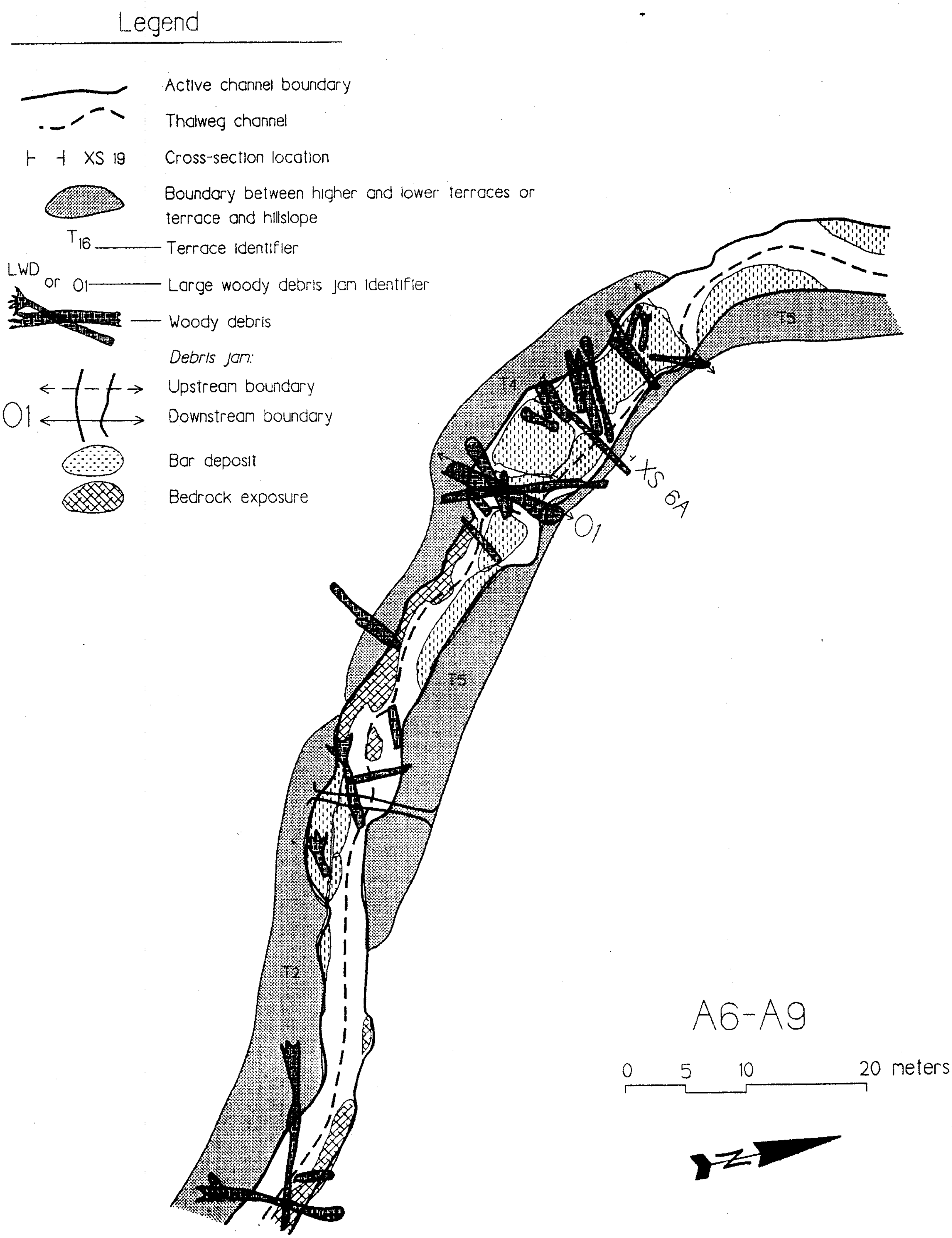

Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or O1
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
O1
Downstream boundary
Bar deposit
Bedrock exposure
T5
T4
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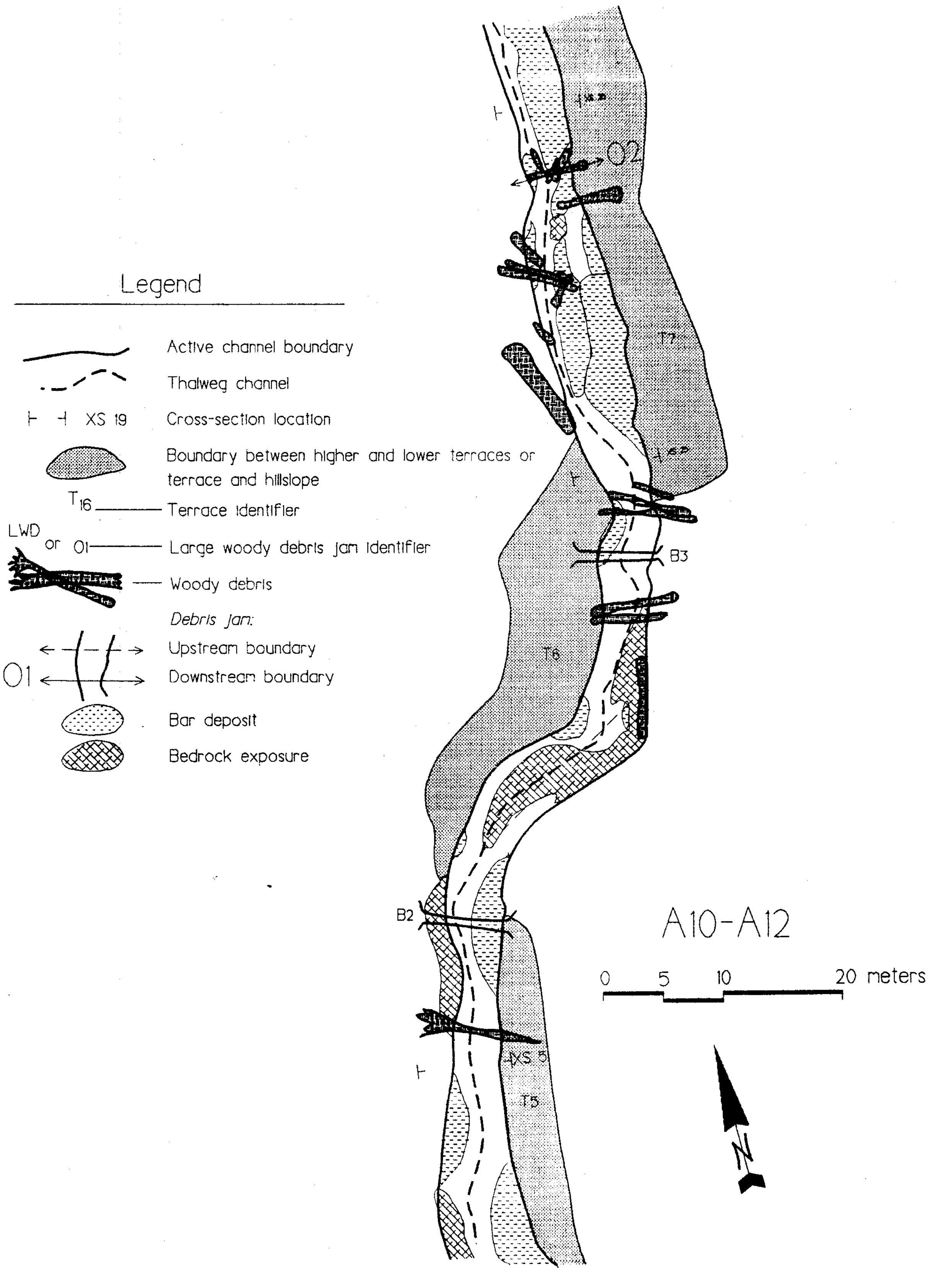
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Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
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Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
O1
Downstream boundary
Bar deposit
Bedrock exposure
O2
T7
B3
T6
B2
XS 5
T5
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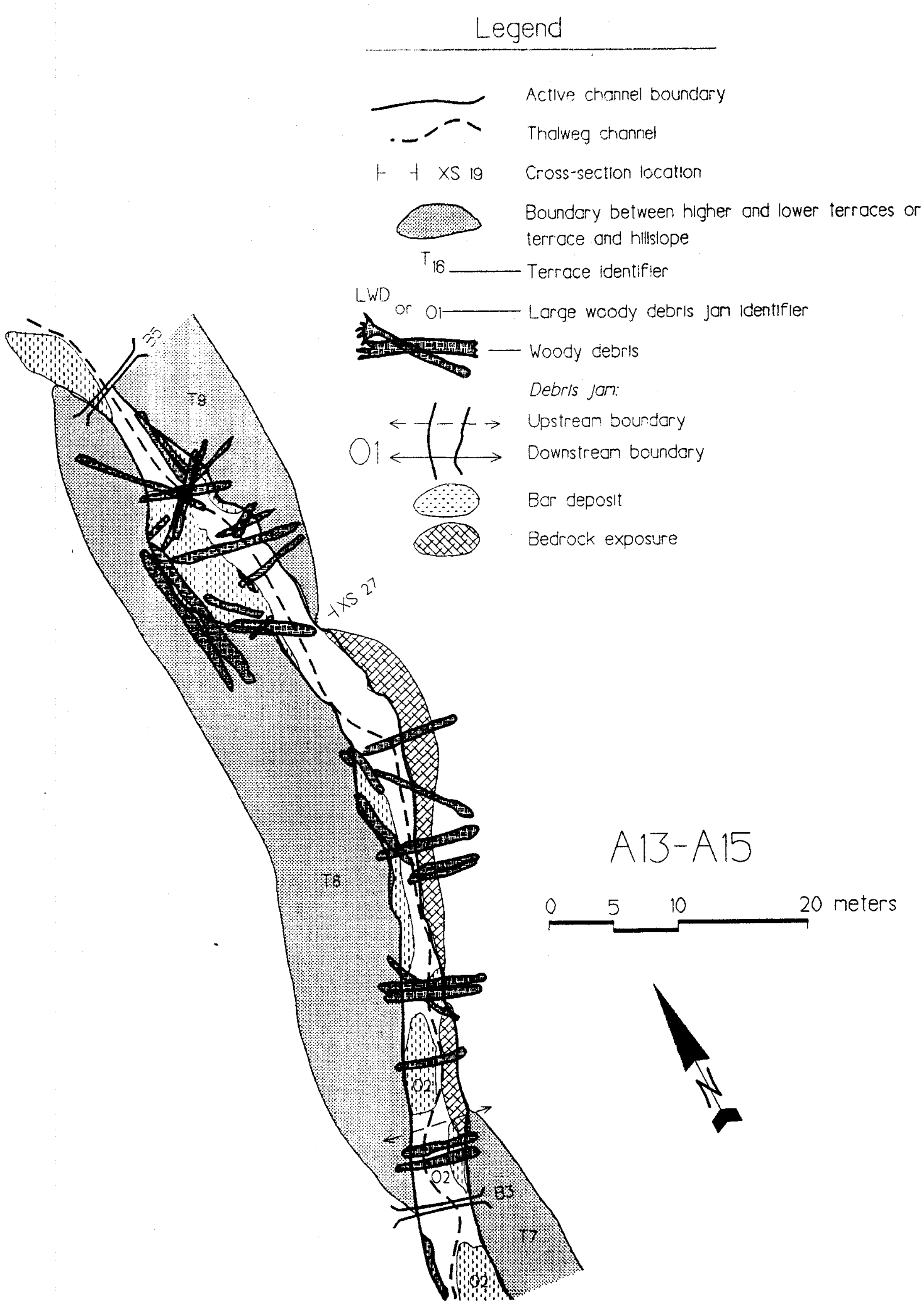
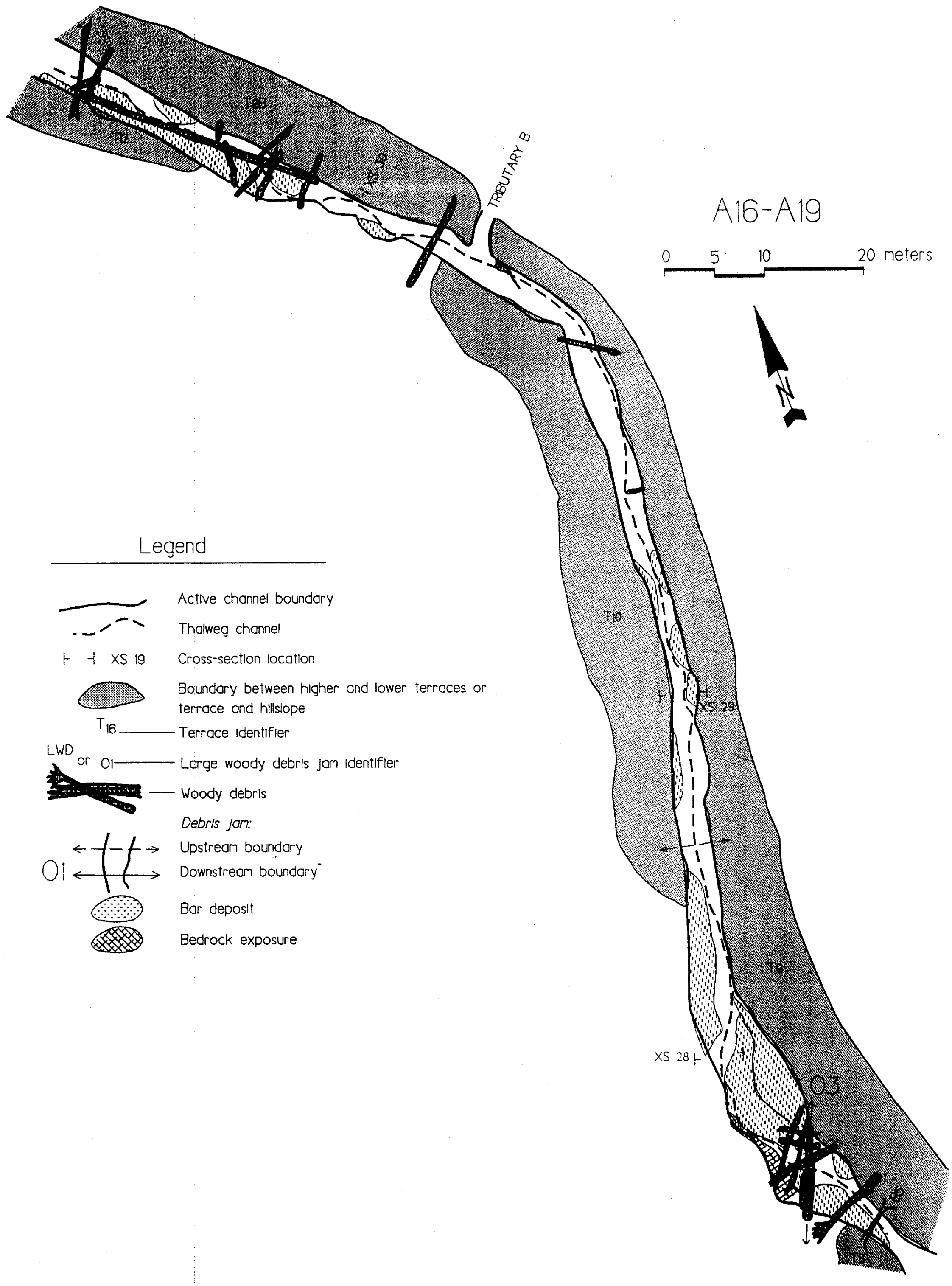
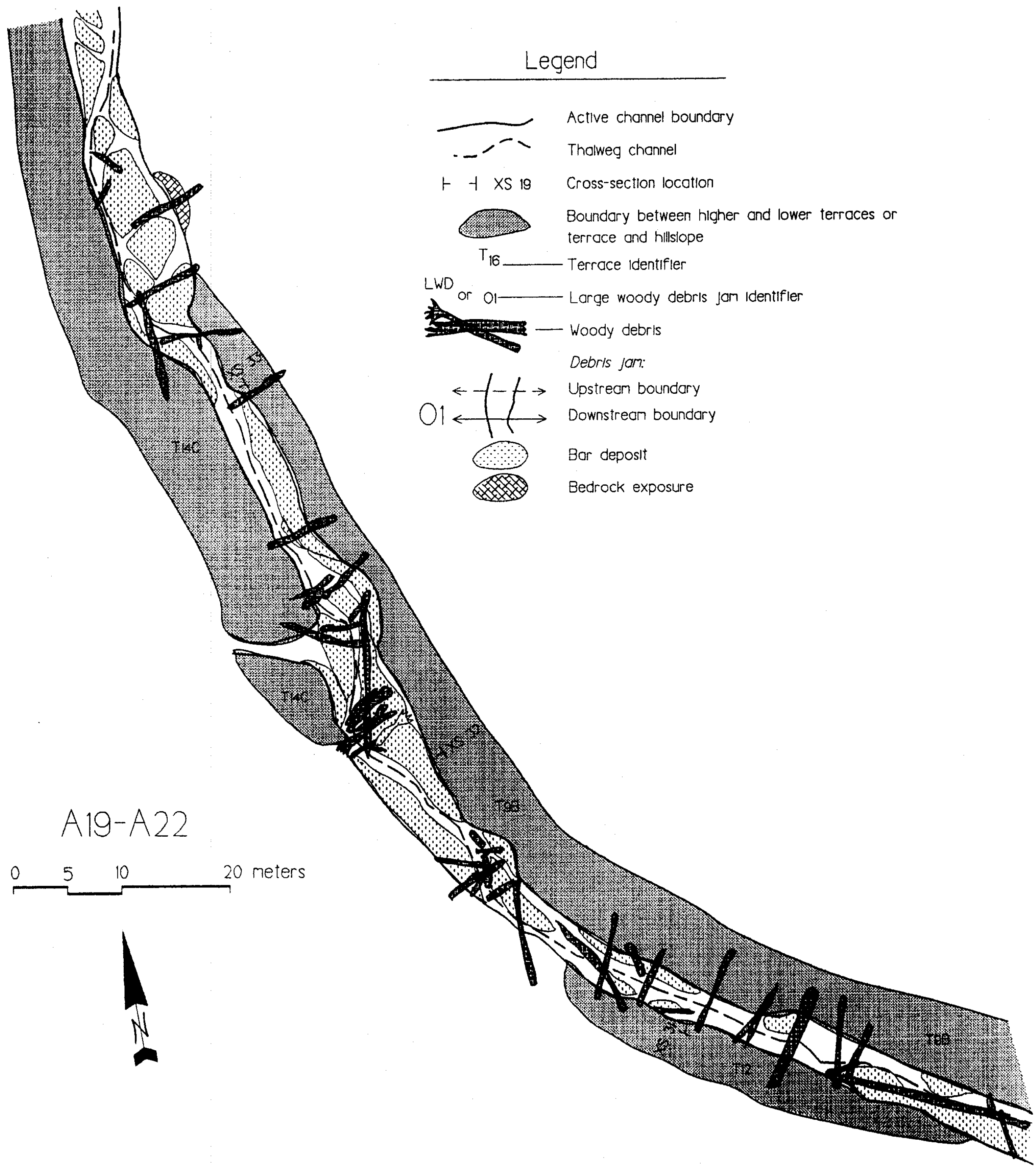
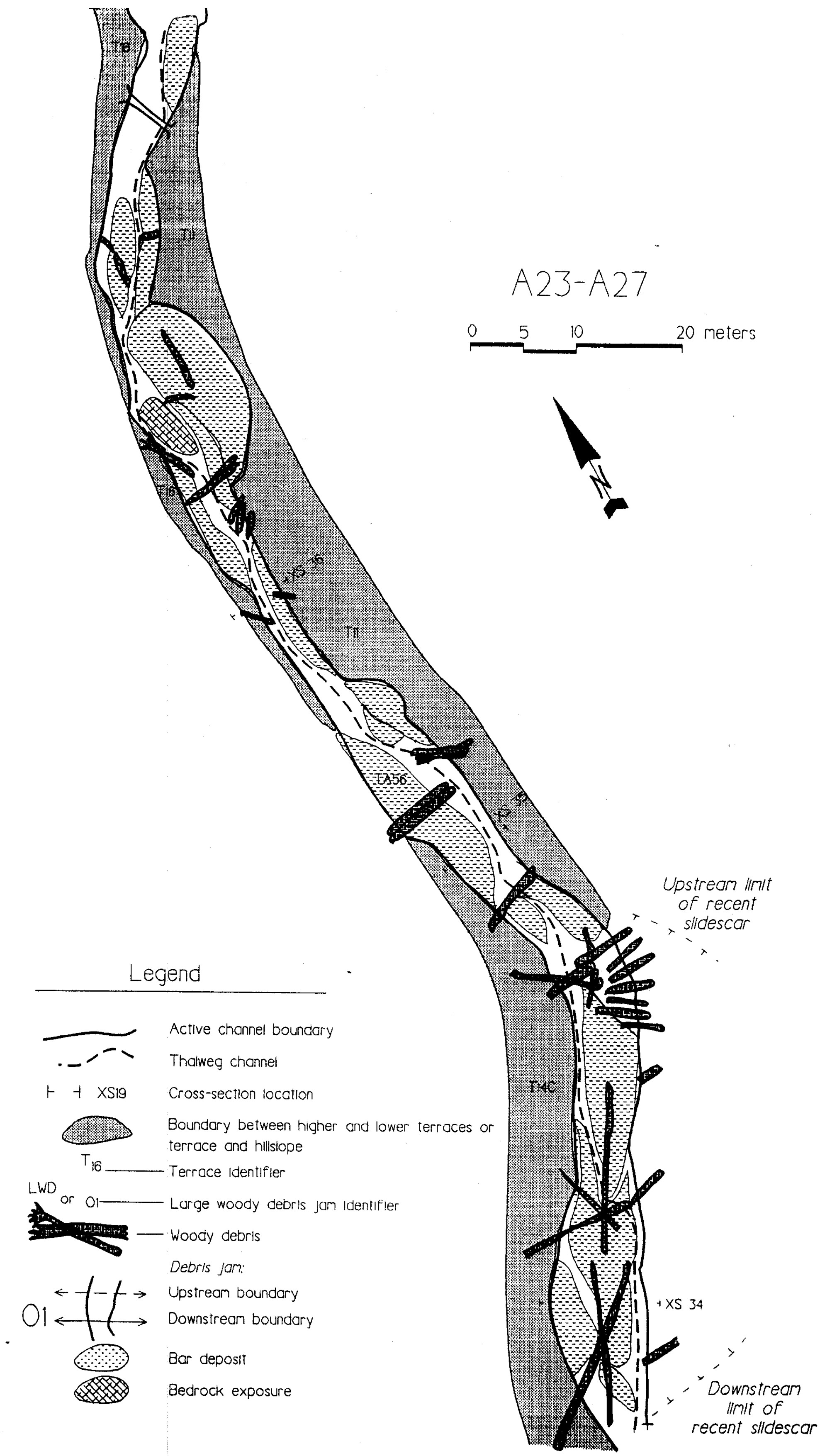


Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or 01
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
01
Downstream boundary
Bar deposit
Bedrock exposure
35
T9
XS 27
T8
02
02
B3
T7
02
A13-A15
0 5 10 20 meters
N

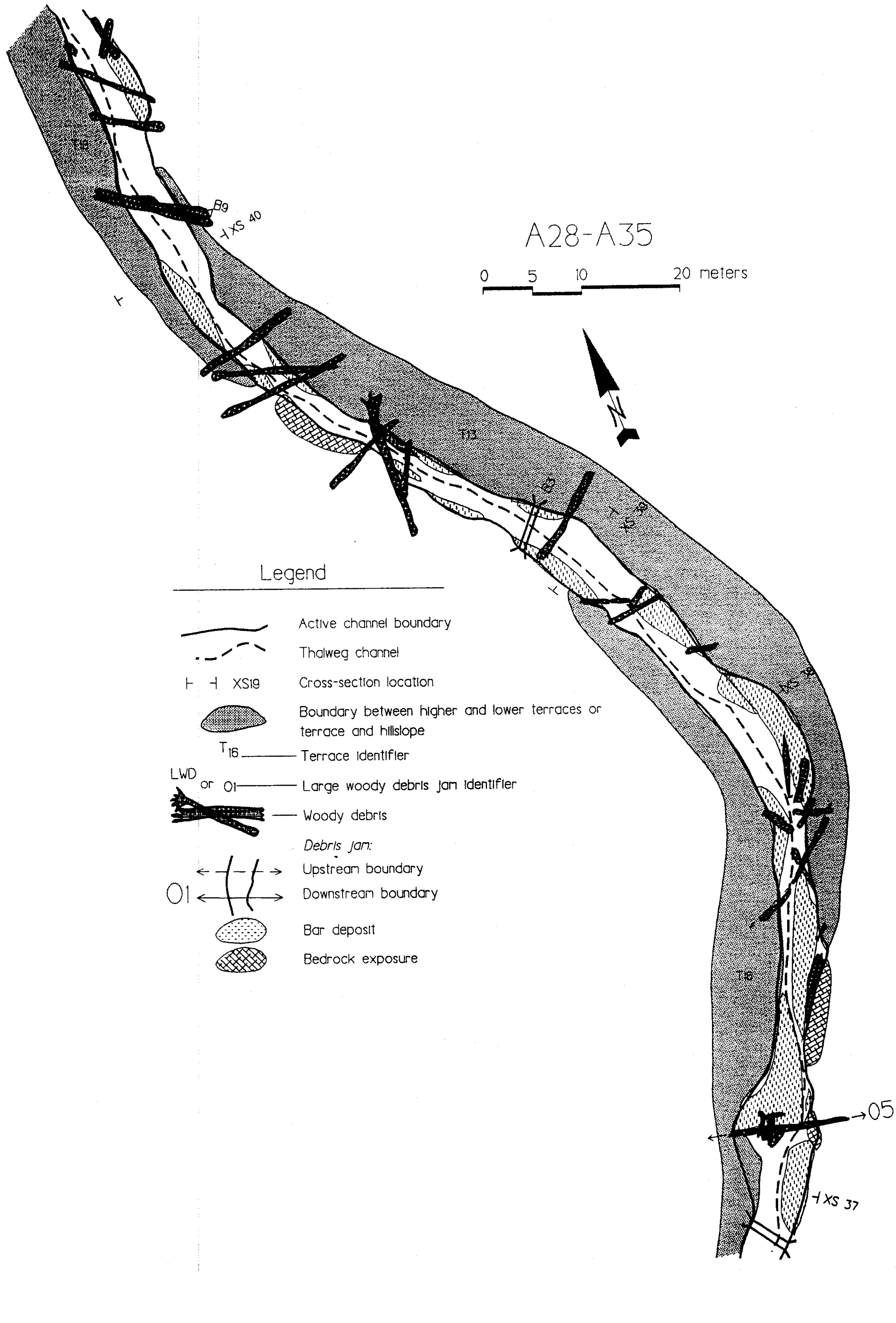

A16-A19
0 5 10 20 meters
N
TRIBUTARY B
T10
XS 29
XS 28
O3
Legend
Active channel boundary
Thalweg channel
XS 19 Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16 Terrace identifier
LWD or O1 Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
O1 Downstream boundary
Bar deposit
Bedrock exposure

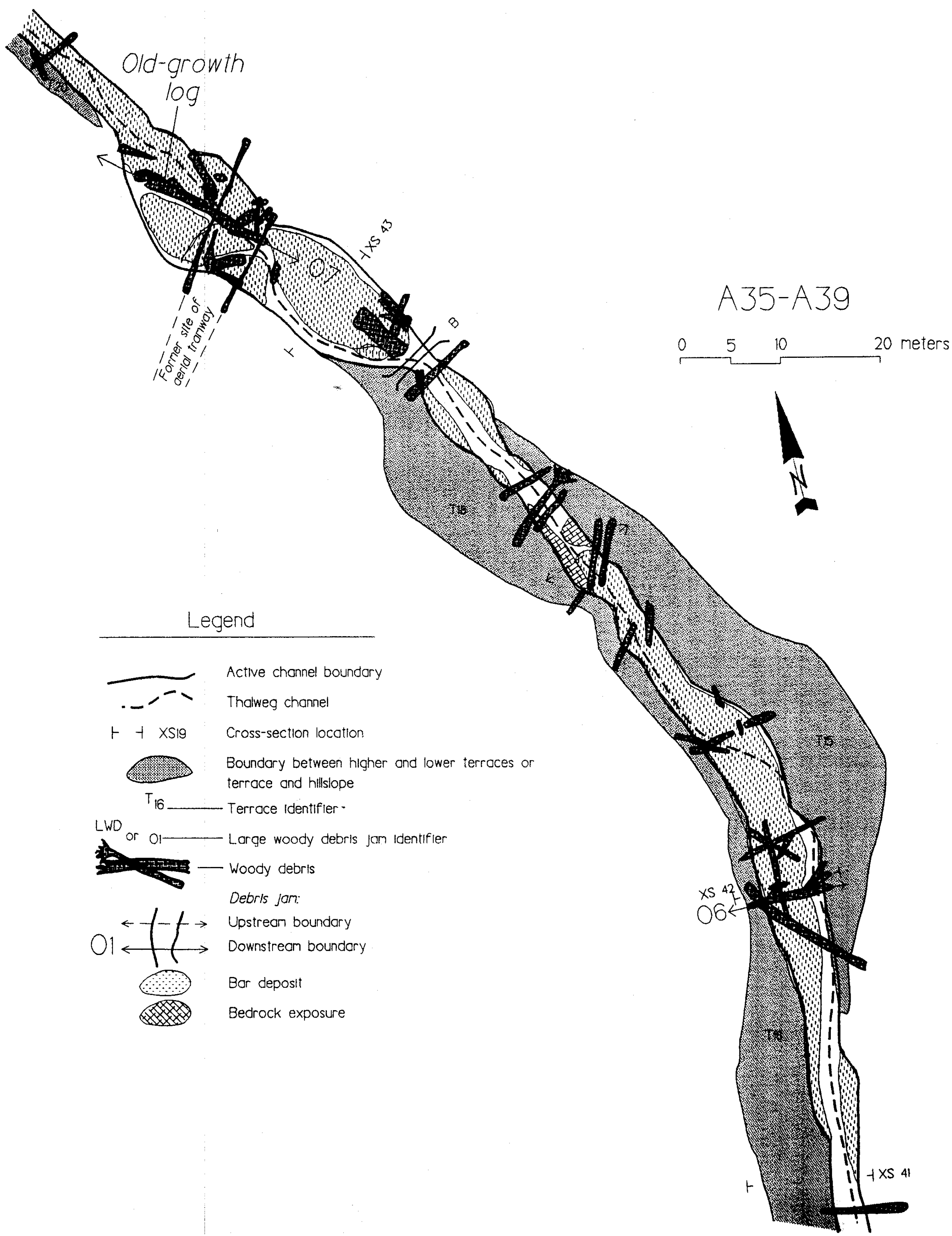


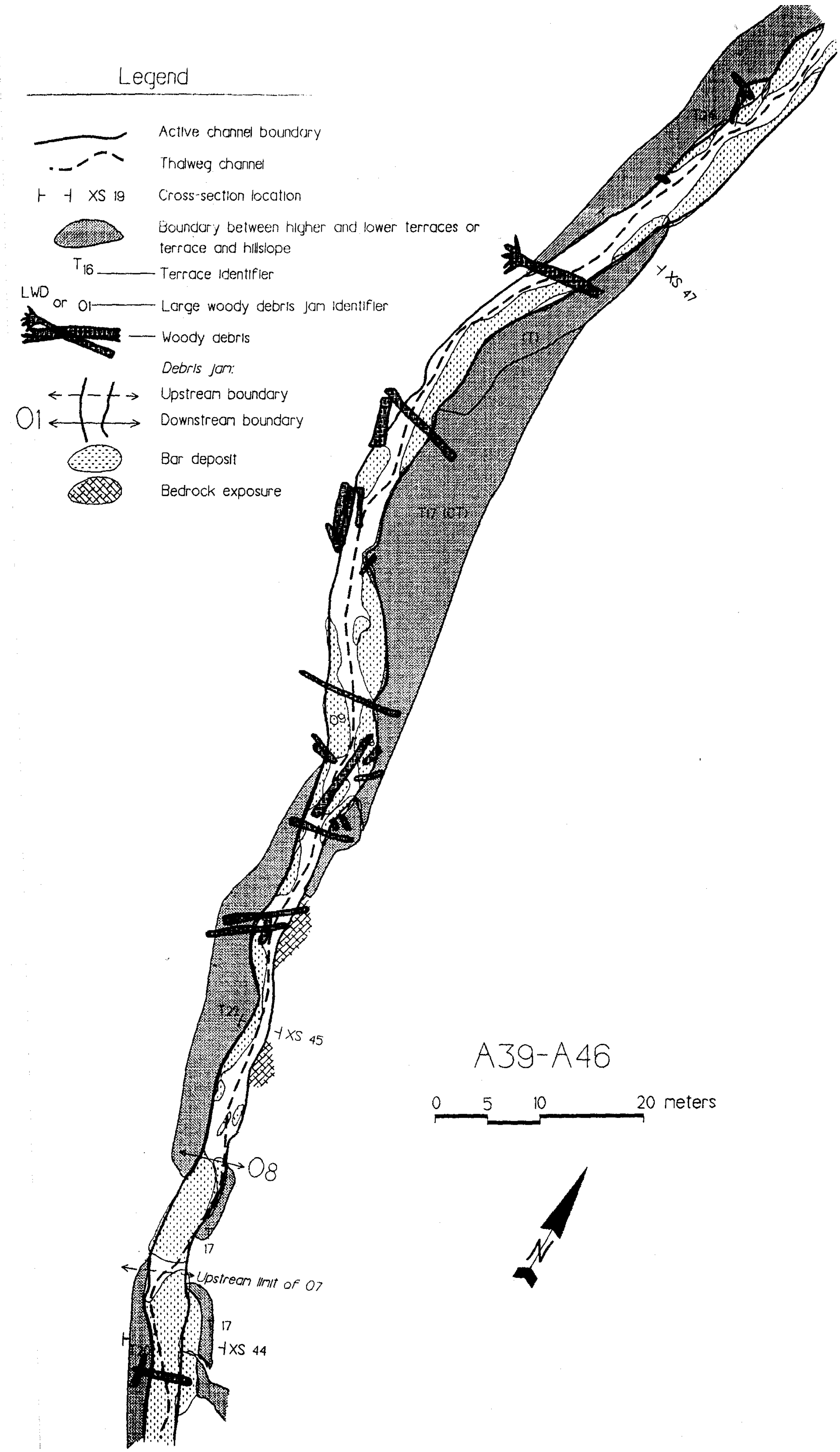
Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or 01
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
01
Downstream boundary
Bar deposit
Bedrock exposure
T14C
T14C
T9B
T9B
T12
A19-A22
0 5 10 20 meters
N



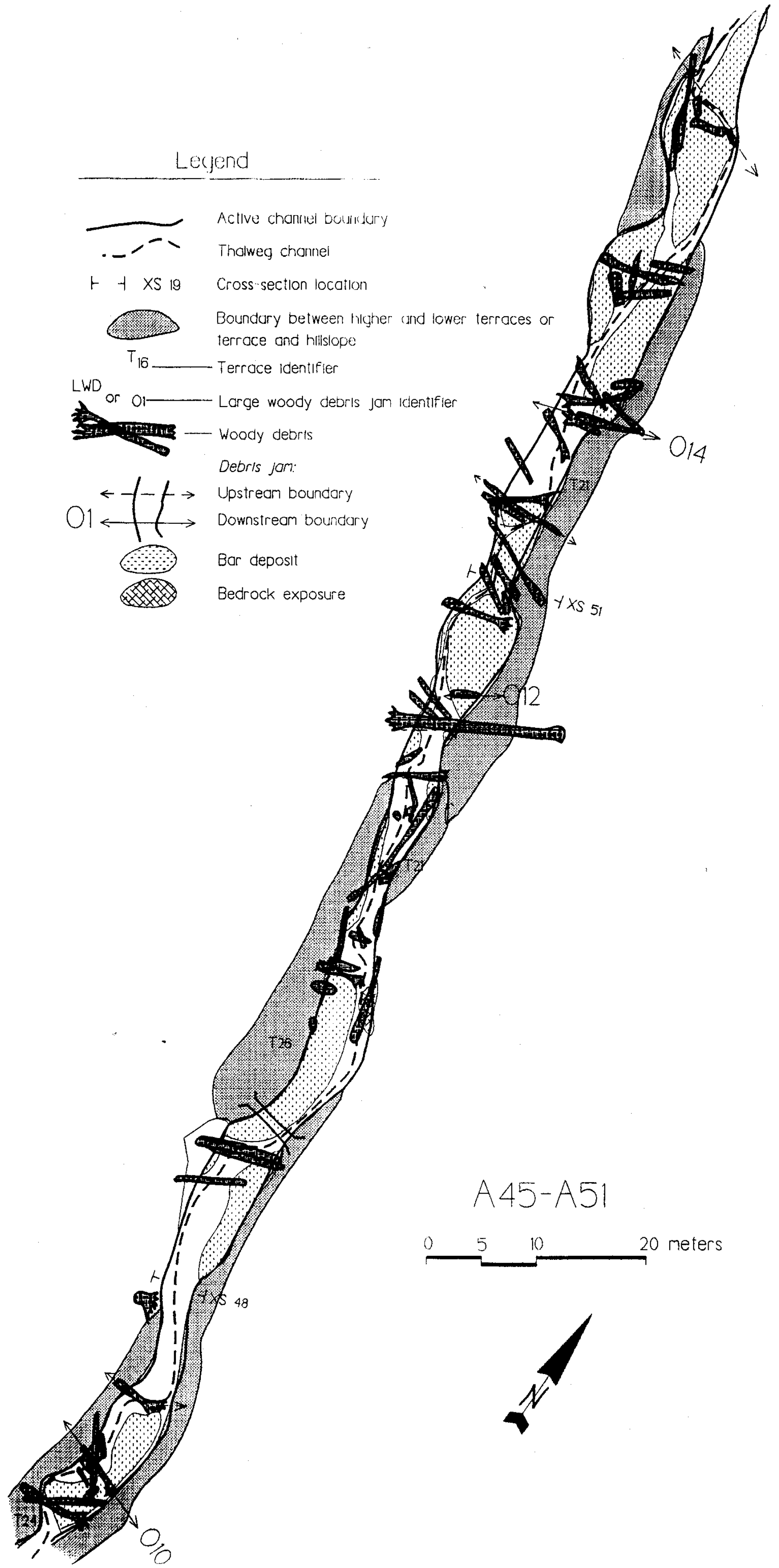
A23-A27
0 5 10 20 meters
N
Upstream limit of recent slidescar
Downstream limit of recent slidescar
XS 34
T4C
Legend
Active channel boundary
Thalweg channel
XS19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or 01
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
01
Downstream boundary
Bar deposit
Bedrock exposure

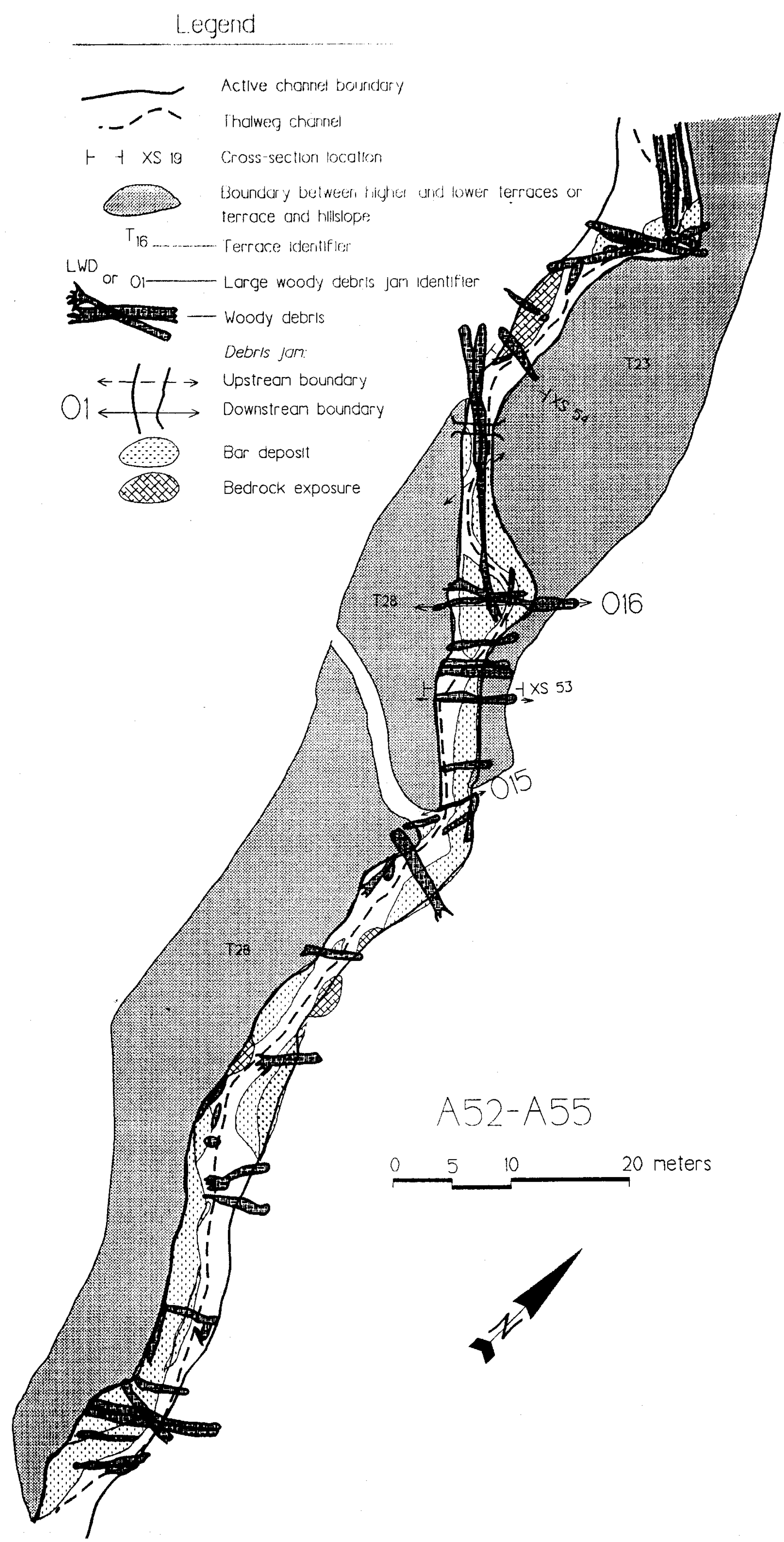

A28-A35
0 5 10 20 meters
N
T18
T13
B9
XS 40
B3
XS 39
XS 38
T18
05
XS 37
Legend
Active channel boundary
Thalweg channel
XS19 Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16 Terrace identifier
LWD or 01 Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
01 Downstream boundary
Bar deposit
Bedrock exposure


A35-A39
0 5 10 20 meters
N
Old-growth log
Former site of aerial tramway
XS 43
07
B
T16
T15
XS 42
06
XS 41
Legend
Active channel boundary
Thalweg channel
XS19 Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16 Terrace identifier
LWD or 01 Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
01 Downstream boundary
Bar deposit
Bedrock exposure

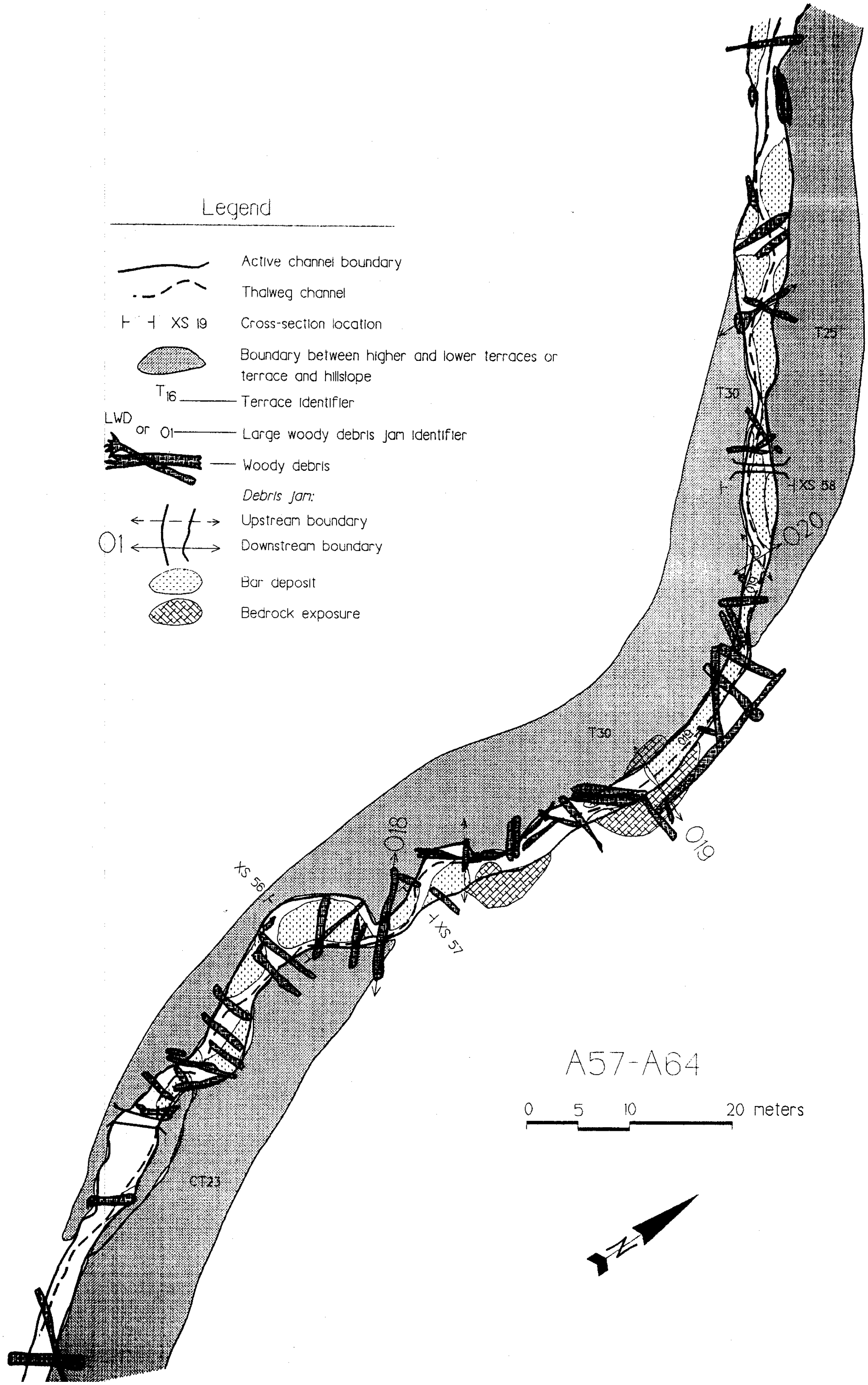


Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or 01
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
01
Downstream boundary
Bar deposit
Bedrock exposure
XS 47
XS 45
08
17
Upstream limit of 07
XS 44
A39-A46
0 5 10 20 meters
N

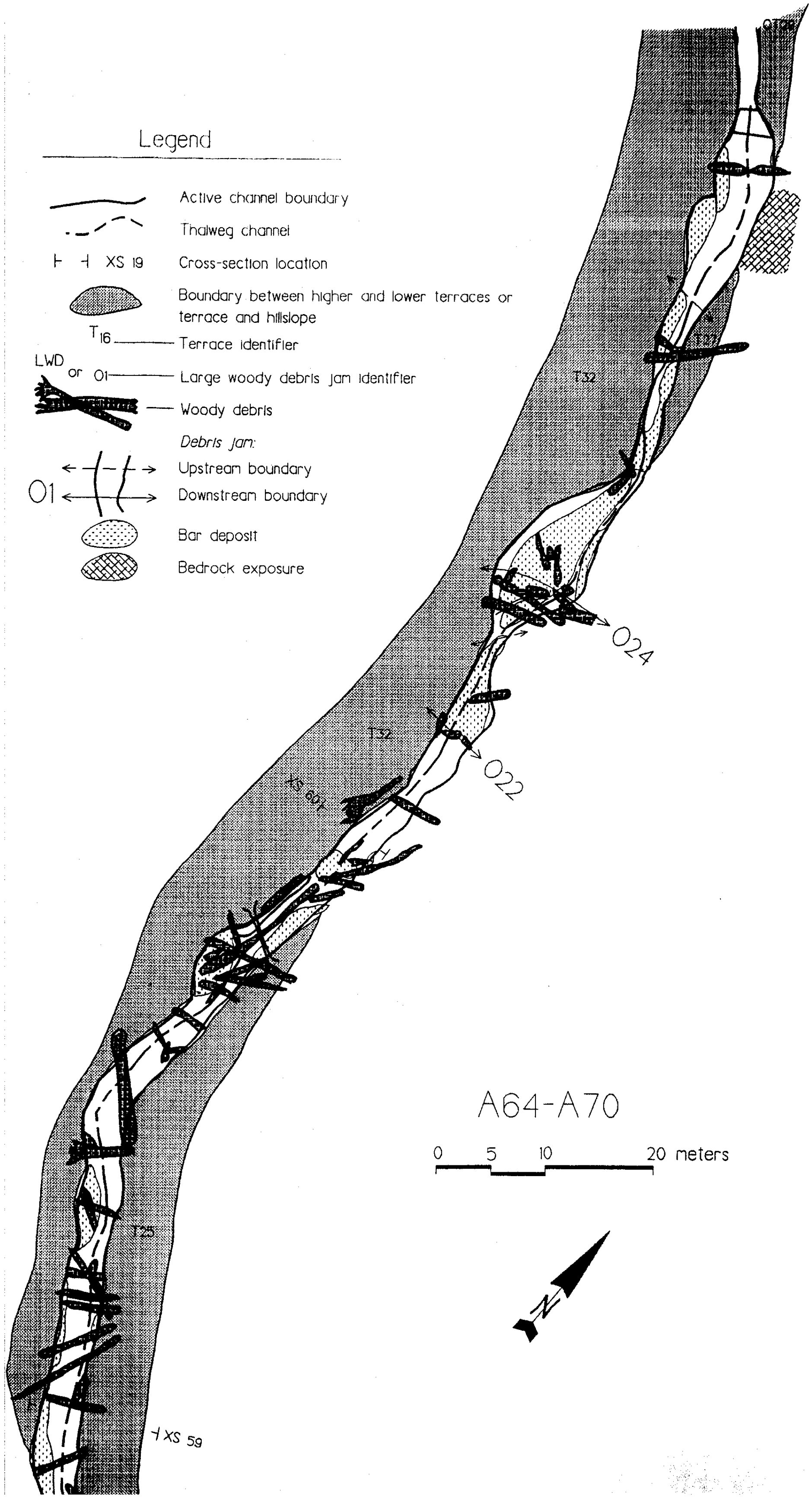

Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or O1
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
O1
Downstream boundary
Bar deposit
Bedrock exposure
O14
T21
XS 51
O12
T21
T25
XS 48
T24
O10
A45-A51
0
5
10
20 meters
N

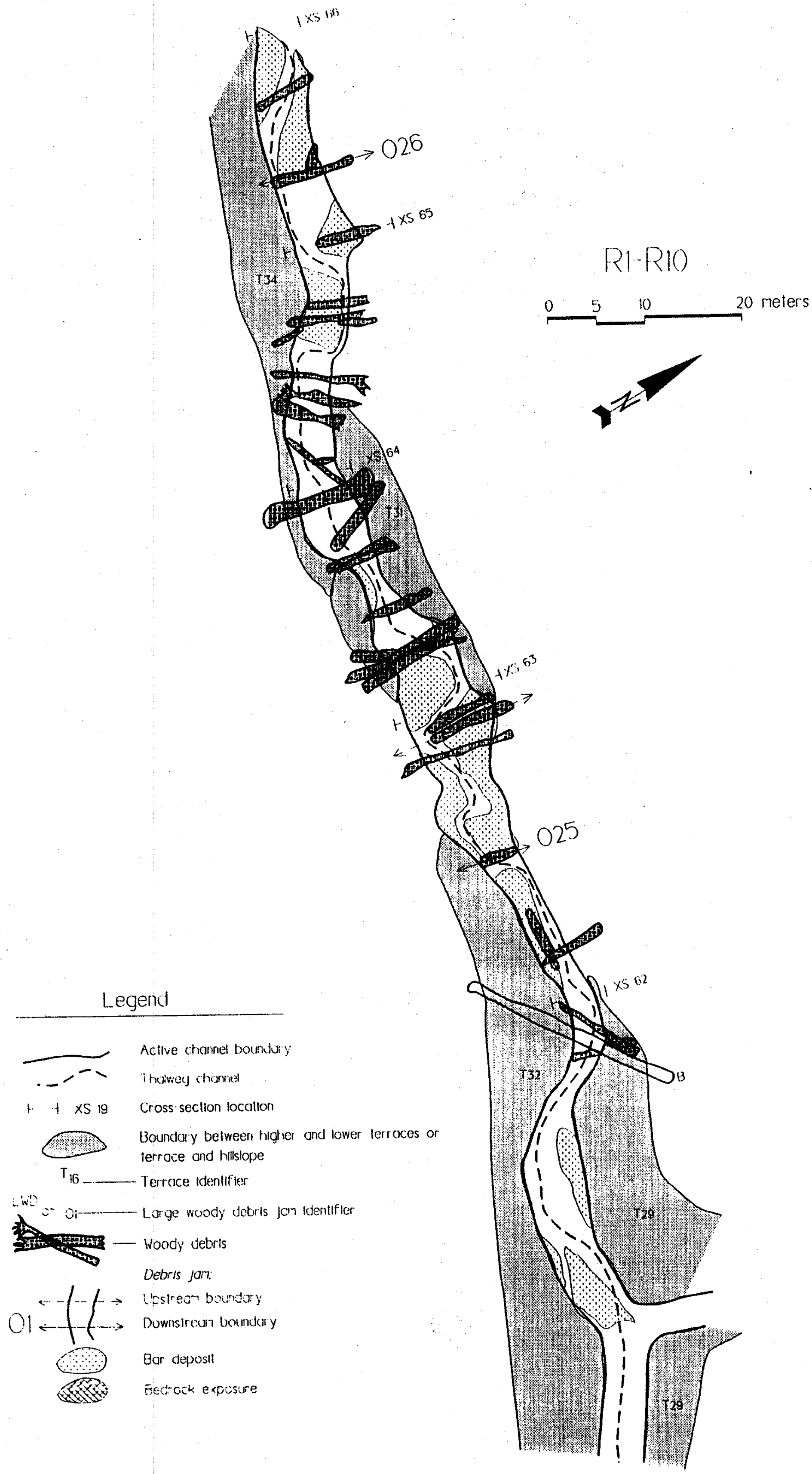


Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or O1
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
O1
Downstream boundary
Bar deposit
Bedrock exposure
T23
XS 54
T28
O16
XS 53
O15
T28
A52-A55
0 5 10 20 meters
N

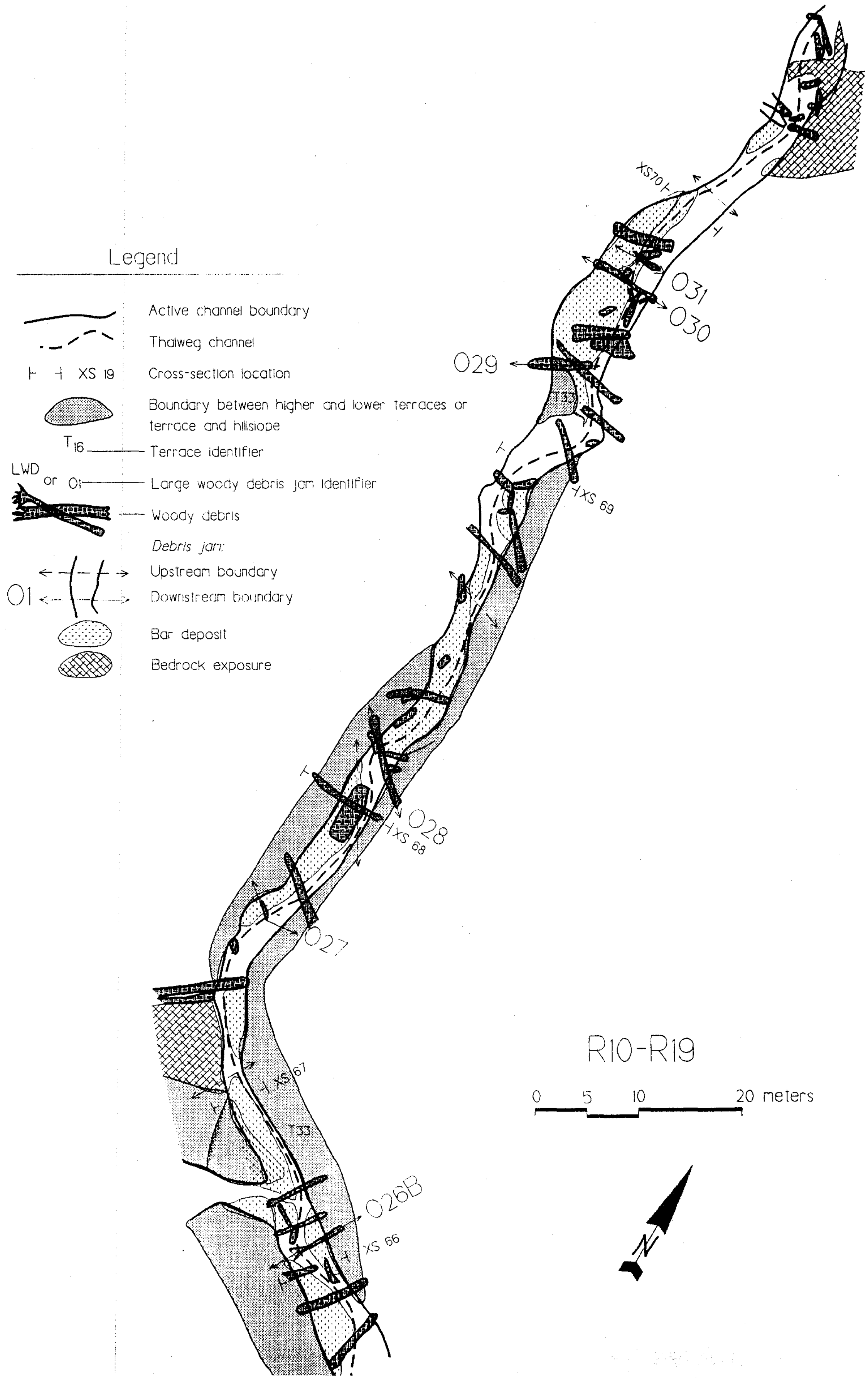


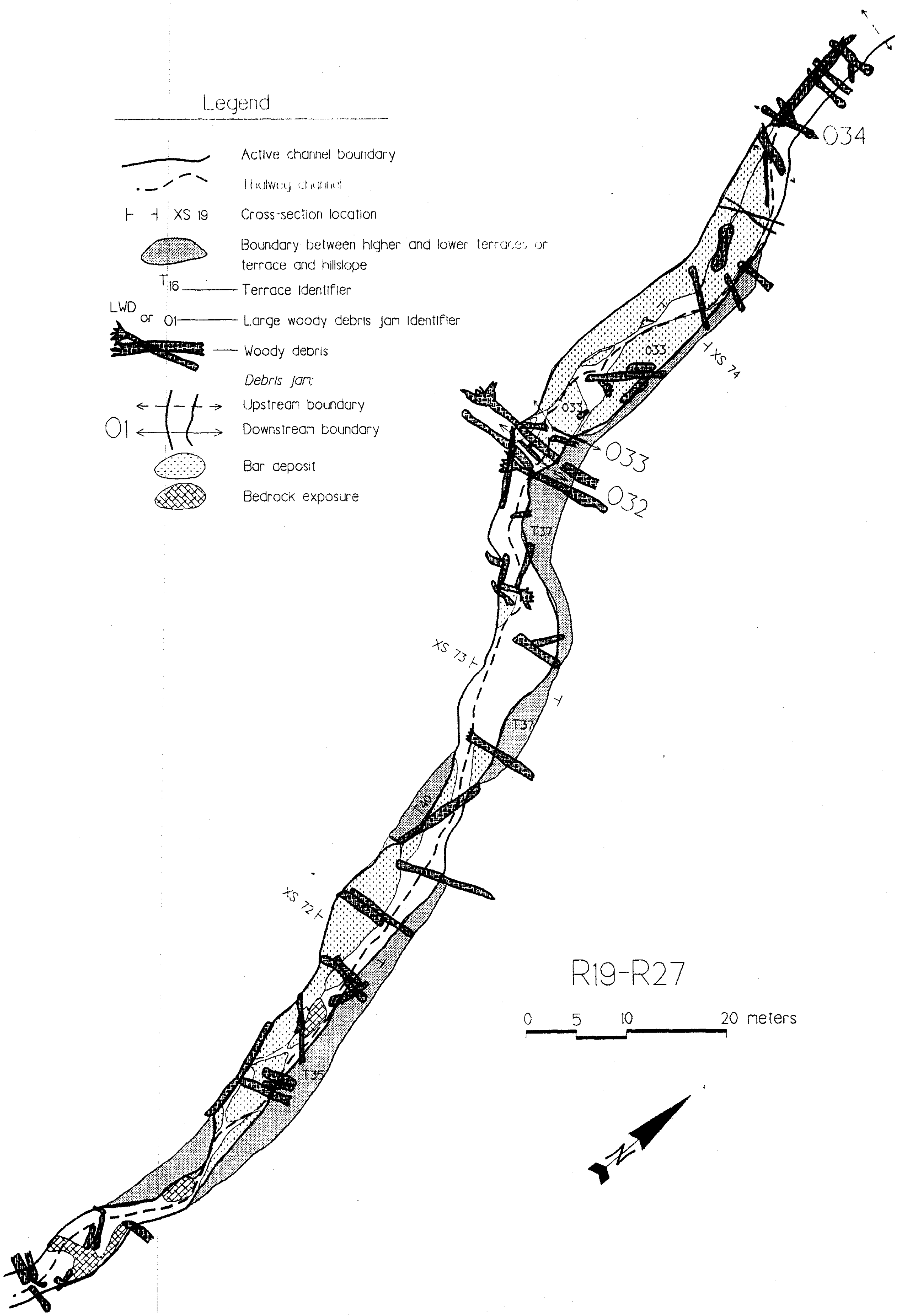
Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or O1
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
O1
Downstream boundary
Bar deposit
Bedrock exposure
T25
T30
XS 58
O20
T30
O19
O18
XS 56
XS 57
CT23
A57-A64
0 5 10 20 meters
N

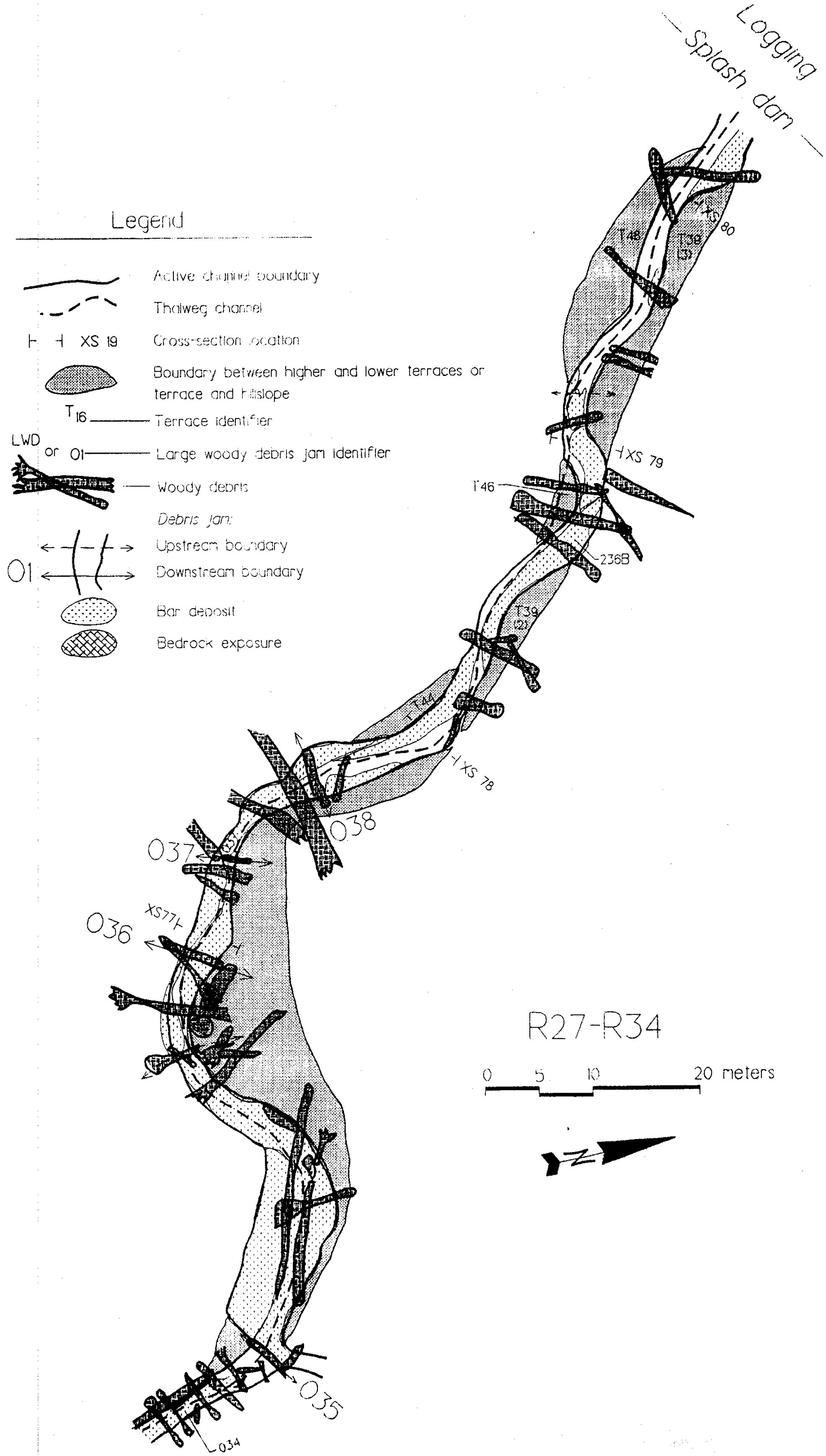

Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or 01
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
01
Downstream boundary
Bar deposit
Bedrock exposure
T32
T27
O24
T32
O22
XS 60
T25
XS 59
A64-A70
0
5
10
20 meters
N



XS 66
O26
XS 65
T34
R1-R10
0 5 10 20 meters
N
XS 64
T31
XS 63
O25
XS 62
T32
B
T29
T29
Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or O1
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
O1
Downstream boundary
Bar deposit
Bedrock exposure


Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or O1
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
O1
Downstream boundary
Bar deposit
Bedrock exposure
XS70
O31
O30
O29
T33
XS 69
O28
XS 68
O27
XS 67
T33
O26B
XS 66
R10-R19
0 5 10 20 meters
N


Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or 01
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
01
Downstream boundary
Bar deposit
Bedrock exposure
034
033
033
033
032
XS 74
T37
XS 73
T37
XS 72
T35
R19-R27
0 5 10 20 meters
N


Logging
Splash dam
Legend
Active channel boundary
Thalweg channel
XS 19
Cross-section location
Boundary between higher and lower terraces or terrace and hillslope
T16
Terrace identifier
LWD or 01
Large woody debris jam identifier
Woody debris
Debris jam:
Upstream boundary
01
Downstream boundary
Bar deposit
Bedrock exposure
XS 80
T48
T39 (3)
XS 79
T46
236B
T39 (2)
T44
XS 78
038
037
XS77
036
035
034
R27-R34
0
5
10
20 meters
N