Geomorphic Setting of the Ventura River Watershed,

and

History of the Ventura River
Near the Robles Diversion, California.

Report by:

Brian Cluer, Ph.D.
Fluvial Geomorphologist
Habitat Conservation Division
Southwest Region
NOAA - National Marine Fisheries Service
Santa Rosa, CA

Prepared on August 19, 2010
1. Introduction

This report describes the watershed and fluvial geomorphologic processes, and the channel history, relevant to the setting of the Robles Diversion and fish passage facilities within the Ventura River. The intention of this report is to provide an understanding of the location and the geomorphic effect of the Robles diversion with respect to the recent fluvial history of the Ventura River. A publication by Warrick and Mertes (2009) of the US Geological Survey provides a sound basis for describing the setting and relative behavior of the Ventura River watershed regarding sediment yield from basins, and is a key resource used for interpreting the series of historic aerial photographs of the Ventura River, in the vicinity of the Robles Diversion, used in this report. This reference (Warrick and Mertes, 2009) is attached as Appendix I to this report.

An analysis of the geomorphic processes and channel history of the Robles Diversion and fish passage facilities site indicates that the Robles diversion and fish passage facilities have been built entirely within relatively recent fluvial deposits of the Ventura River. Even over the brief time period described by the available aerial photographs (1939 to present), soils map, and the subsurface alluvial samples, it is apparent that the footprint of the facility was recently occupied by active river channels, immediately prior to the initial construction of the Robles Diversion in 1957-59.
2. Nature of the Ventura River Watershed

Section 2 of this report discusses Ventura River watershed processes, which underpin a conceptual understanding of channel processes at the Robles diversion (discussed in Section 3).

The geographic location of the Ventura watershed combines a tectonically active setting with relatively young and weak rocks, extreme climate (ENSO storm cycles), and wildfire regime, to create one of the most dynamic watersheds and river systems in California. This is a region of torrential storms and violent debris flows that have been the subject of popular literature on human interactions with natural processes, which become tragic disasters (e.g. The Control of Nature, by John McPhee).

2.1 Geography and Geology

The Ventura River watershed lies in the Western Transverse Ranges (WTR) of southern California (Figure 1). It drains 226 square miles of rugged mountainous terrain, where steep streams flow onto relatively flat valley areas as they exit the mountains. The watershed includes mountains which reach just over 6000 feet elevation. The WTR is a tectonically active, semiarid region characterized by a high rate of denudation, generally attributed to the region’s highly fractured and relatively weak sedimentary rocks (Warrick and Mertes, 2009).
The underlying geology of the Ventura River watershed (Figure 2) is characterized by relatively recent (Eocene and younger) and relatively weak marine sedimentary rocks that have been uplifted and later highly fractured by ongoing tectonic processes (Rockwell et al., 1984). The geologic materials making up the watershed are easily erodible, and most of the soil in the basin is relatively impervious, soft, and easily eroded (Corps of Engineers, 1971).
2.2 Climate and Hydrology

The climate of the area is characterized by cool winters with occasional storms and hot, dry summers. Average annual precipitation is ~70 cm in the upper mountains and ~40 cm near sea level, as a result of orographic effects. Over 90% of the annual precipitation occurs during the winter period; December-April. Heavy precipitation occurs in the area, especially when enhanced by moisture from the subtropical eastern Pacific, which can be influenced by the El Niño- Southern Oscillation (ENSO; Andrews et al., 2004). Rainfall in the area produces ephemeral, although occasionally torrential, stream flows. The largest storms are correlated with ENSO cycles, which are quasi-periodic, typically returning at 5 year intervals. ENSO storm periods vary in intensity, so
it is common that the large storms in California recur in approximate increments of 5 years, such as 10 years, 15 years, and occasionally as much as 20 years.

2.3 Sediment Transport Events

Andrews and Antweiler (2006) found that in the southern California streams, 72-90% of all daily mean discharges sufficient to entrain the average sized bed particle occurred during an El Niño phase. A majority of the total number of days with bed motion occurred during relatively few years, about 1 in 5. Periods lasting 2-5 years with few or no days of discharge sufficient to exceed the initial motion threshold are common in the coastal streams of Southern California. Consequently, the ENSO cycle is the primary driver of sediment transport events in the region.

2.4 Sediment Yield

Southern California is famous in the earth sciences and land use disciplines for debris flows (Graf, 2002), which raise havoc with infrastructure and property, and occasionally take lives. This is because of the combination of occasional torrential storms and a highly erodible terrain that yields tremendous quantities of sediment. Sediment yields from the Western Transverse Ranges of California are 2- to 10 times greater than the surrounding areas of California (Warrick and Mertes, 2009). The high sediment yield areas in this region are consistently composed of weakly consolidated bedrock and the highest rates of tectonic uplift. Warrick and Mertes (2009) concluded that sediment yield estimates for the Ventura River have been previously underestimated by approximately 50%, because the area produces about 2 times the sediment that one
would estimate using conventional methods based on scaling sediment yields from nearby watersheds to the Ventura watershed. They also concluded that about half of the total suspended sediment discharge from the Western Transverse Ranges is generated in about 10% of the watershed area. (See also Brownlie and Taylor 1981; Hill and McConaughy 1988.)

2.5 Wildfire and Vegetation

In addition to the tectonic, geologic, topographic, and climatic processes operating in the Ventura River watershed that drive the production of sediment, chaparral wildfire has a profound effect on sediment yield. Florsheim et al., (1991) showed that sediment yield increased by over an order of magnitude the year or two following wildfires in the Ventura watershed. To understand the relative importance of wildfire, I catalogued wildfires in the Ventura watershed (Figure 3). Ventura County is approximately 144,000 acres total area. Wildfires larger than approximately 10,000 acres have occurred on average about every 12 years in the watershed, with periods between ranging from 3 to 31 years. Consequently, vegetation and wildfire can add an additional pulse to the primary ENSO driven sediment event in the Ventura River watershed. Stream morphology is changed locally following wildfire sediment delivery events, although this debris is transported downstream with subsequent flooding (Florsheim et al., 1991; Keller et al., 1997).
Acres Burned (log scale)

Figure 3. History of wildfires in the Ventura River Watershed. Wildfires larger than approximately 10,000 acres have occurred on average about every 12 years in the watershed, with periods between ranging from 3 to 31 years. Data from CalFire FRAP database, current through 2009.

3. Channel Processes

The watershed processes discussed in Section 2, above, describe a watershed in which the geology and climate produce high erosion rates, thus delivering large sediment loads to streams. Sediment delivery events reoccur in intervals driven primarily by ENSO storm cycles, and secondarily by wildfire. The ENSO storms return on average approximately every 5 years, but may reoccur at increments of 5 years, such as approximately 10 or 15 years, while the wildfire events reoccur over somewhat longer time intervals, also driven by ENSO climate cycles conducive to rapid vegetation growth and periodic drying.
The watershed drivers create a Ventura River in which storms sufficient to mobilize river beds and shift channel locations and patterns reoccur relatively frequently, followed by relatively quiescent periods during the intervening dry years. The stream channel is altered by the transport of large quantities of coarse sediment during El Niño storms and wildfires in the watershed. These processes cause the Ventura River, where not confined by valley walls in the mountainous areas, to meander across its entire valley, and at any one step in time, one or more channels can be found in completely different locations, particularly with respect to fixed infrastructure.

The Ventura River in the vicinity of the Robles Diversion is a location where the relatively confined valley upstream gives way to an open valley downstream. In effect, there is no single channel with fixed location in this reach of the Ventura River. Graf (2002) explained that “alluvial fans originate where confined streams flow from mountain fronts onto relatively open basin floors, as the result of a combination of channel widening and channel migration.”

The fan area is where the stream’s capacity to transport coarse sediment suddenly drops, and coarse sediment is deposited in the [then] active channel. An active channel is often blocked by sediment and the stream finds a new (or former) course (or multiple courses) elsewhere on the fan. Because the valley walls are receded, there is space for many channels, islands, meanders, etc.; some recent and active, and some in temporary retirement until a significant sediment delivery event shifts the focus of deposition, forcing a different channel to become dominant or eroding a new one. Alluvial fan channels are some of the most dynamic, and hazardous, channels known (Graf, 2002). Cooke (1984) identified five hazards associated with alluvial fans from his work in the
Los Angeles area: unpredictable individual flows, variations between flows, debris flows which cause sedimentation problems, channel migration and avulsion, and long periods of inactivity which mask the channel behavior and the associated hazards.

4. Recent Geomorphic History of the Ventura River Channel at the Robles Diversion

Given the conceptual geomorphic framework developed above, it is possible to discuss the Robles site (Figure 4) in its formative context. Historical aerial photographs were rectified to a common geographic coordinate system, and the recently active channels were traced to highlight channel locations for each of these snapshots in time. The channel traces were placed on the 1947 photograph to show the spatial range of channel locations for the pre-Robles diversion period for which aerial photographs were reviewed (Figure 5), and on the 2009 photograph for the post-Robles diversion period (Figure 6).

4.1 Plan View of Channel Locations

In the pre-Robles period, the Ventura River occupied a progressively widening belt (Figure 5), expanding in the downstream direction. This wide channel zone started a few hundred feet upstream from where the present day diversion is located. The channel widens progressively, a pattern indicative of an alluvial fan, and coincides with the opening of the Ventura River canyon onto its valley, and loss of channel confinement (see the topographic map, Figure 7).
Figure 4. 1947 aerial photograph of the Ventura River in the vicinity of the Robles diversion. The river flows from top (north) to bottom (south).
Figure 5. Channel boundaries captured by the 1939 and 1947 aerial photographs, each a snapshot of time, for the pre-Robles construction period, placed on the 1947 aerial photograph.
Figure 6. Channel boundaries captured in 4 aerial photographs, each a snapshot of time, for the post-Robles construction period, placed on the 2009 aerial photograph. Notice the restricted channel movement around the diversion facilities compared to the pre-Robles period.
In the post-Robles period, the channel belt is relatively narrow and the channel location is more spatially stable, upstream from and through the diversion (Figure 6). It is confined by the training structures upstream, and levees downstream, by repetitive sediment dredging from the channel in the forebay of the dam, and by the concentration of energy and scour capacity of flows over the dam itself. The channel continues to fan out downstream from the dam, although not as much as it did in the pre-Robles period.

This analysis culminated in my developing a map depicting the outlines of the recently active channel (Figure 8). The recently active channel is based on the maximum extents of the visibly active channels from the aerial photographs, and identification of higher terrace features bounding the fan basin representing earlier fluvial deposits that are being eroded by the current Ventura River. The outline of the recently active channel as determined by this methodology corresponds closely with the spatial pattern of soils related to fluvial processes, discussed in the next section.
Figure 7. Topographic map of the Ventura River as it exits the confined valley (top, north) and opens onto the alluvial fan (bottom, south). Source: USGS, 2000.
Figure 8.  2009 aerial photograph depicting the recently active channel zone, outlined in red. The recently active channel is based on the maximum extents of the visibly active channels from the aerial photographs, and identification of higher terrace features bounding the fan basin representing earlier fluvial deposits that are being eroded by the current Ventura River.
4.2 Borehole View of Fan Deposits

Boreholes drilled and logged for the Robles diversion construction plan documents (Figure 9; BOR, 1960) provide additional information on the history of Ventura River channel processes. Every borehole log is composed entirely of non-indurated fluvial sediments; deposit young enough that they are not cemented together. These relatively young deposits are from the ongoing alluvial fan process that has dominated this location for some time. The holes extend beyond what was, at that snap shot of time, the active river channel. (See section 4.3 Soils of this Area for further discussion of the significance of the distribution of these boreholes.)
Figure 9. Borehole geologic logs for the vicinity of Robles diversion site. Note that the holes extend beyond what was at that time the active channel, and that the deposits are essentially the same regardless of their location. This indicates that the Ventura River periodically occupied this entire footprint in relatively recent time. Figure from BOR, 1960.
4.3 Soils of the Area

Soils within the outline of the recently active channel area (from Figure 10) are all associated with fluvial landforms. These soils are developed on parent materials that are classified as alluvial deposits, derived from sedimentary rocks. There is close spatial correspondence between the fluvial soils types and the outline of recently active channel area mapped from channel locations and aerial photo interpretation of landforms.

Structural features of the Robles diversion including the intake and bypass gates, forebay and subsequently built fish passage facilities were digitized from the 2009 aerial photograph, which was rectified to the same geographic coordinates as the soils map. These structural features are also depicted on Figure 10. It is evident that the diversion features (including the timber cutoff wall, intake and bypass gates, afterbay, and subsequently built fish passage facilities) were built within soils units that are of fluvial origin and classification.
Table 1. Soils in the vicinity of the Robles diversion. Soils within the outline of the recently active channel area (from Figure 10) are all associated with fluvial landforms. These soils are developed on parent materials that are classified as alluvial deposits, derived from sedimentary rocks. Soils source: U.S. Department of Agriculture, Natural Resources Conservation Service, 2008.

**AnC--Anacapa gravelly sandy loam**
- Landform(s): alluvial fans, alluvial plains
- Parent material: alluvium derived from sedimentary rock
- Slope gradient: 2 to 9 percent

**CrC--Cortina stony sandy loam**
- Landform(s): alluvial fans, inset fans, valleys
- Parent material: alluvium derived from sedimentary rock
- Slope gradient: 2 to 9 percent

**OsD2--Ojai stony fine sandy loam**
- Landform(s): alluvial plains, fan remnants, valleys
- Parent material: alluvium derived from sedimentary rock
- Slope gradient: 2 to 15 percent

**Rw--Riverwash**
- Landform(s): drainageways, valleys
- Parent material: alluvium
- Slope gradient: 0 to 5 percent

**TeF--Terrace escarpments**
- Landform(s): terraces
- Parent material: alluvium derived from sedimentary rock
- Slope gradient: 30 to 50 percent

**38--Orthents-Fluvents complex**
- Landform(s): alluvial plains, terraces
- Parent material: alluvium
- Slope gradient: 0 to 15 percent

**W--Water**
Figure 10. Soils map of the area; descriptions are included in Table 1. Note the spatial correspondence between soils of fluvial origin and the outline of the recently active channel zone (Figure 8). The Robles diversion and its afterbay are depicted in georeferenced location, and lay within the recently active channel zone. Source: U.S. Department of Agriculture, Natural Resources Conservation Service, 2008.
5. Summary and Conclusions

The Ventura River watershed yields sediment at a high rate, in what is regarded as a highly active geologic area. This is due to a combination of ongoing tectonic uplift, weak rocks, and extreme storm cycles exacerbated by wildfire. The site of the Robles diversion on the Ventura River is within an alluvial fan area, where stream channels are typically very dynamic as they respond to episodes of sediment delivery and infrequent flashy storms.

The relatively short history of channel dynamics evident in six aerial photographs shows that the Ventura River occupied a wide area of the valley in the vicinity of the Robles diversion and appurtenant structures over the past eight decades, and that the river was more dynamic before the infrastructure and its operations began modifying sediment transport and channel migration processes in the vicinity of the Robles diversion. Borehole logs from the footprint on which the Robles structures were built show that the deposits are all fluvial, and young enough to be uncemented. The soils map of the Robles vicinity verifies the spatial correspondence of the zone of recent channel activity with river derived parent materials and soils derived from periodic Ventura river flows.

The Robles diversion and fish passage facilities have been built entirely within recently active fluvial deposits of the Ventura River. But for the facilities as they were constructed, the Ventura River would continue to utilize a significantly wider active area, particularly during high flow events, and that area would periodically include the footprint where the Robles diversion was constructed. In effect, the footprint of the Robles Diversion (including the timber cutoff wall, intake and bypass gates, afterbay, and subsequently built fish passage facilities) falls within the boundaries of the recent fluvial
sediments which are the result of the active fluvial geomorphic processes described in Sections 2 and 3 of this report. Several lines of evidence developed and discussed in this report converge on a conclusion that the Robles diversion and its operations has made the Ventura River channel less active within its previously active zone, and the future delivery of coarse sediment following the future removal of Matilija Dam will likely increase channel dynamics in this location with the river periodically re-occupying previously occupied portions of the active channel zone, including the area currently occupied by the Robles diversion and the related fish passage facilities.
References Cited


Florsheim, J.L., Keller, E.A., and Best, D.W., 1984.  Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, southern California.  GSA Bulletin; v. 95; no. 12; p. 1466-1474


U.S. Army Corps of Engineers, 1971.  Flood Plain Information, Ventura River (including Coyote Creek), Ventura County, California.

U.S. Bureau of Reclamation, 1960. Ventura River Project, Ventura County, California.


Geological Society of America Bulletin

Sediment yield from the tectonically active semiarid Western Transverse Ranges of California

Jonathan A. Warrick and Leal A.K. Mertes

Geological Society of America Bulletin 2009;121;1054-1070
doi: 10.1130/B26452.1

Email alerting services click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article

Subscribe click www.gsapubs.org/subscriptions/ to subscribe to Geological Society of America Bulletin

Permission request click http://www.geosociety.org/pubs/copyrt.htm#ga to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes

© 2009 Geological Society of America
Sediment yield from the tectonically active semi-arid Western Transverse Ranges of California

Jonathan A. Warrick1† and Leal A.K. Mertes2§
1USGS Western Coastal and Marine Geology, 400 Natural Bridges Drive, Santa Cruz, California 95060, USA
2Department of Geography and Institute for Computational Earth System Science, University of California, Santa Barbara, California 93106, USA

ABSTRACT

Sediment yields from the world’s rivers are generally highest from steep drainage basins with weak lithology, active tectonics, or severe land-use impacts. Here, we evaluate sediment yields from the Western Transverse Ranges of California in an attempt to explain why they are two- to tenfold greater than the surrounding areas of California. We found that suspended-sediment yields across the gauged basins of the Western Transverse Range during 1969–1999 varied by approximately an order of magnitude (740–5300 t/km²/yr). Similarly, fine-sediment concentrations for normalized discharge rates varied by almost two orders of magnitude (e.g., 1.3–110 g/L for the mean annual flood) for 11 previously unmonitored drainages of the Santa Ynez Mountains. Areas with high sediment yields consistently have weakly consolidated bedrock (Quaternary-Pliocene marine formations) and are associated with the highest rates of tectonic uplift of the region (>5 mm/yr). These regions are important to the sediment discharge budgets, because ~50% of the total suspended-sediment discharge from the Western Transverse Range is estimated to be generated within these regions, even though they represent only ~10% of the total watershed area. Previous estimates of suspended-sediment discharge from the Ventura River have likely been underestimated by ~50% because the gauging station is located immediately upstream of a high sediment yield region. We also found a significant and positive correlation between sediment yield and the percentage of a watershed with grassland and agricultural land use. These results suggest that there is adequate variation within the lithology, tectonics, and land use of the broader Western Transverse Range geologic province to induce large variations in sediment yield at the local scale.

INTRODUCTION

Landscape and climatic factors influence denudation and sediment discharge from rivers over many spatial and temporal scales. Sediment yield is generally greatest in areas with high relief, high rates of uplift, and intensive land use, although sediment deposition within the landscape and floodplains may reduce sediment fluxes and yields with distance from erosion sources (Trimble, 1981; Meade, 1982; Milliman and Syvitski, 1992; Reid and Dunne, 1996; Aalto et al., 2003; Kettner et al., 2007). Precipitation and other climatic factors appear to have nonlinear effects on sediment yield (Langbein and Schumm, 1958; Hicks et al., 1996; Molnar, 2001; Peizhen et al., 2001). Rare events or slight changes in climate may be responsible for dramatic changes in sediment discharge rates for some rivers (e.g., Inman and Jenkins, 1999; Sommerfield et al., 2002; Galewsky et al., 2006; Milliman et al., 2007), while other rivers are less influenced by these climatic factors (e.g., Hicks et al., 2000).

River sediment fluxes from watersheds less than ~1000 km² are gauged less frequently than larger rivers—especially with respect to their vast number—even though their combined fluxes appear to be important to global biogeochemistry (Milliman and Syvitski, 1992; Lyons et al., 2002). Because of the lack of gauging data and apparent homogeneity of landscape and climate over the small, regional scales represented in these basins, material fluxes may be assumed to be relatively uniform—or to follow simple scale-dependent rules—across these smallest of watersheds (e.g., Schwalbach and Gorsline, 1985; Milliman, 1995; Meigs et al., 1999). In light of this, local (~10 km) variations in exhumation of twofold over 10⁴ to 10⁷ yr have been calculated in the Andes (Safran et al., 2006), and differences in land use over these spatial scales are known to alter sediment yield and river sediment budgets (Trimble, 1997; Gabet and Dunne, 2002). Intensive monitoring of small river basins has shown that denudation may be significantly variable and related to drainage-basin characteristics such as bedrock lithology or land use (Reid and Dunne, 1996; Hicks et al., 2000), although these results can be influenced by the length of monitoring and the kinds of hydrologic events that were and were not observed (Inman and Jenkins, 1999; Galewsky et al., 2006). Unfortunately, these studies are rare due to the time and cost necessary for such work.

Here, we investigate sediment yield in the drainages of the Western Transverse Ranges (Fig. 1), which have been previously estimated to be up to an order of magnitude greater than other drainages of Southern California (Scott and Williams, 1978; Brownlie and Taylor, 1981; Inman and Jenkins, 1999). These rates have been attributed to a general weakness in the Western Transverse Range lithology compared to the other California mountain ranges. Here, we explore this further by addressing two research questions about the Western Transverse Ranges: (1) Are sediment yields variable over scales of small (10–100 km²) drainage basins? (2) If variable, are differences in sediment yield related to drainage-basin properties (e.g., lithology, land use, relief, and precipitation)? To answer these questions, we monitored fine-sediment discharge from a series of previously unmonitored streams of the Western Transverse Range and constructed both suspended-sediment and water discharge budgets from Western Transverse Range watersheds from historical U.S. Geological Survey (USGS) data.

Study Area

The Western Transverse Ranges of California (Fig. 1) are a tectonically active, semi-arid region characterized by a high rate of denudation,
Within the lowlands, many areas have been converted to agriculture (citrus orchards and row crops) and mixed-use urban areas.

The climate of the area is characterized by cool winters with occasional storms and hot, dry summers. Average annual precipitation is ~70 cm in the upper mountains and ~40 cm near sea level, as a result of orographic effects (Fig. 3). Rainfall in the east–west–trending Transverse Ranges is enhanced by southerly winds during North Pacific storms (Mo and Higgins, 1998; Farnsworth and Warrick, 2007), and rain shadows are observed on leeward sides of ranges, such as north of the Santa Monica and San Gabriel Mountains (Fig. 3). Heavy precipitation occurs in the area, especially when enhanced by moisture from the subtropical eastern Pacific (Mo and Higgins, 1998), which can be influenced by El Niño–Southern Oscillation (ENSO; Andrews et al., 2004).

Erosion processes in the Western Transverse Range have been identified as primarily dry ravel and mass movements (Rice, 1982), while stream bank erosion and sheet flow also contribute to sediment yield (Hill and McConaughy, 1988; Taylor, 1981). Mass movements have been noted in the area during and after intense rainfall (Rice and Foggin, 1971; Raphael et al., 1995), while dry ravel is understood as a relatively constant process occurring during dry periods (Taylor, 1981). This dry ravel accumulates along hillslopes and in stream channels and is flushed out by floods (Rice, 1982; Lavé and Burbank, 2004). These combined processes are nonlinear functions of wind, soil moisture, and precipitation duration, amount, and intensity and are very difficult to generalize in simple models (Rice, 1982).

Land cover and land use in the Western Transverse Range are thought to influence denudation and rates of landsliding. For example, Gabet and Dunne (2002) found that Western Transverse Range denudation rates increased when native chaparral was replaced by non-native annual grasses, which dominate grazed rangelands. Pinter and Vestal (2005) showed that landslide incidence during the 1997–1998 winter was greatest in grazed portions of Santa Cruz Island—one of the Northern Channel Islands (Fig. 1B)—and that landslide incidence increased with decreasing vegetation density. These results are consistent with wetland sedimentation observations in the Northern Channel Islands by Cole and Liu (1994), where the introduction of annual grasses during European colonization is shown to have coincided with ~tenfold increases of landscape denudation. Within the broader Southern California region, urbanization has been shown to increase storm discharge and alter the primary locations of sediment yield, which can alter sediment budgets.
Figure 2. Geologic map of the Western Transverse Range study area (after Saucedo et al., 2000). Watershed boundaries are shown for the three main drainage areas with thick dashed lines. Rock uplift rates from dated marine terraces are shown and increase significantly from west to east (after Duvall et al., 2004).
Sediment yield in California

and sediment concentration-discharge relations (Trimble, 1997; Warrick and Rubin, 2007).

Erosion in the study area is further complicated by fire, which can increase sediment yield by over an order of magnitude due to increased dry ravel and rilling (Rice, 1982; Florsheim et al., 1991; Keller et al., 1997). This increased yield typically continues through a few years as brush root systems rot (Rice, 1982). Stream morphology is often changed after a fire, as pools fill with coarse sediment, although this debris is transported to downstream reaches and the coastal margin with subsequent flooding (Florsheim et al., 1991; Keller et al., 1997). Although fire may have dramatic effects on short-term sediment yields, investigation of 21 Eastern Transverse Range (Fig. 1A) basins has shown that fire will increase long-term sediment yield (i.e., the yield measured over periods greater than the fire recurrence interval of ~40 yr) by only ~10% of mean unburned yields (Taylor, 1981). Similarly, Lavé and Burbank (2004) suggested that fire may increase the long-term sediment discharge of Eastern Transverse Range river basins by only 20% over the value measured during intervals without fire.

METHODS

Water and Sediment Yields from USGS Stations and Dammed Basins

Water and suspended-sediment discharge budgets were constructed from USGS gauging station data, which extend over many decades for the study area (Fig. 1B; Table 1). Suspended-sediment discharge was evaluated using (1) USGS computations of daily suspended-sediment discharge (typically 1969–1978), and (2) suspended-sediment discharge rating curves for years without these daily computations. Rating curves were fit through suspended-sediment sampling data using the locally weighted scatter smoothing (LOWESS) technique of Cleveland (1979), which is preferred when there is curvature in the log(discharge)–log(concentration) relationship (e.g., Hicks et al., 2000). The LOWESS technique fits a nonlinear curve through a two-dimensional (in this case, instantaneous discharge and concentration) data set by calculating locally best-fit values using two weighting functions and a local polynomial function of fit (Fig. 4). A complete set of rating curves for the study area is provided in the GSA Data Repository.¹

The concentrations derived from LOWESS ($C_{\text{LOWESS}}(Q)$) were corrected for logarithmic transform bias ($A_{\text{log}}$) and daily averaging bias ($A_{\text{daily}}$):

$$C_t = A_{\text{log}} A_{\text{daily}} C_{\text{LOWESS}}(Q).$$  \hspace{1cm} (1)

The logarithmic transform bias ($A_{\text{log}}$) was calculated based on a technique of Ferguson (1987), which estimates the arithmetic means from the LOWESS-derived geometric means. These techniques suggest that:

$$A_{\text{log}} = \exp(2.651s^2),$$ \hspace{1cm} (2)

where $s$ is the standard error of the concentration estimates in log units. This correction is appropriate only when residuals are normally distributed.

¹GSA Data Repository item 2009027, Hydrologic and watershed data summaries for the drainage basins of the Western Transverse Ranges, is available at http://www.geosociety.org/pubs/ft2009.htm or by request to editing@geosociety.org.

Figure 3. Average annual precipitation (cm/yr) in Southern California, 1961–1999 (after SCAS, 2000). Watershed boundaries of the study area are shown with thick dashed lines.
distributed, which was the case for the data assessed. However, the standard errors were also an inverse function of discharge (e.g., Fig. 4), and, thus, Equation 2 was applied to the sediment concentration estimates using local ($n = 20$) standard errors.

Finally, the data were corrected for the bias produced by averaging instantaneous flow data into daily values ($A_{\text{daily}}$). As shown by Warrick and Milliman (2003), large intradaily dynamics in discharge exist for the study area, and this variability is not captured in the average daily data published by the USGS. To correct for the effects of this intradaily variability, the LOWESS rating curve was applied to both instantaneous (raw 15 min) and daily average streamflow records for the period 1990–1999, which were compared to find $A_{\text{daily}}$. Values of $A_{\text{daily}}$ are given in the GSA Data Repository (see footnote 1) and range from 1.09 to 1.68, and they are inversely related to watershed drainage area.

Lastly, suspended-sediment discharge ($Q_s$) was computed from daily discharge records using:

$$Q_s = \int Q(t) C_s(t) \, dt,$$

where $Q$ is the river discharge, $C_s$ is the suspended-sediment concentration, and $t$ is time in days. Sediment-load estimates using Equations 1–3 were generally indistinguishable from USGS estimates for the range 1969–1978 (root mean square error [r.m.s.e.]) = 15%–30%).

Daily water and sediment discharge values were then summarized into annual discharge budgets for all gauging stations (tabulated in GSA Data Repository [see footnote 1]). These discharge records were then extended to the interval 1969–1999 so that a consistent time of record could be compared for each station. Extension of records was conducted by use of linear regression of coincidental annual water and sediment loads of adjacent watersheds with high correlation ($all r^2 > 0.9$).

Six USGS stations in the study area were used in the suspended-sediment analyses, and an additional nine stations were used to compute water discharge budgets (Fig. 1B; Table 1). For this work, data from the two Santa Clara River mouth stations (11114000 and 11113920) were combined, since the stations are adjacent, and 11113920 was only sampled when 11114000 was inaccessible due to flooding. For the 10 yr of USGS estimated suspended-sediment loads, the r.m.s.e. between these and our results was 30%. The water discharge calculations have approximately ±15% error.

Finally, sediment yield from dammed basins was assessed using published investigations of reservoir sedimentation. Details of this information are documented in Warrick (2002) and include sedimentation rates from the Piru and

<table>
<thead>
<tr>
<th>USGS station no.</th>
<th>Total drainage area (km$^2$)</th>
<th>Gauge duration (yr)</th>
<th>Average sediment discharge (Mt/yr)$^*$</th>
<th>Average water discharge (Mm$^3$/yr)$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santa Clara River</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Castaic Creek (11108145)</td>
<td>477</td>
<td>29</td>
<td>n.d.</td>
<td>0.27</td>
</tr>
<tr>
<td>Santa Clara River at LA county line (11108500)</td>
<td>1619</td>
<td>43</td>
<td>1.20</td>
<td>0.71</td>
</tr>
<tr>
<td>Piru Creek (11110000/11109800)</td>
<td>1131/1100</td>
<td>61</td>
<td>n.d.</td>
<td>0.89</td>
</tr>
<tr>
<td>Hopper Creek (11110500)</td>
<td>61</td>
<td>51</td>
<td>0.17</td>
<td>0.076</td>
</tr>
<tr>
<td>Sespe Creek (11113000)</td>
<td>650</td>
<td>69</td>
<td>1.51</td>
<td>1.50</td>
</tr>
<tr>
<td>Santa Paula Creek (11113500)</td>
<td>104</td>
<td>72</td>
<td>n.d.</td>
<td>0.31</td>
</tr>
<tr>
<td>Santa Clara River at Montalvo/Saticoy (11114000/1111920)</td>
<td>4185/4084</td>
<td>53</td>
<td>6.84</td>
<td>3.45</td>
</tr>
<tr>
<td>Ventura River</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matilija Creek (11115500)</td>
<td>141</td>
<td>61</td>
<td>n.d.</td>
<td>0.44</td>
</tr>
<tr>
<td>North Fork Matilija Creek (11116000)</td>
<td>40</td>
<td>55</td>
<td>n.d.</td>
<td>0.14</td>
</tr>
<tr>
<td>San Antonio Creek (11117500)</td>
<td>133</td>
<td>34</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>Coyote Creek (11118000)</td>
<td>107</td>
<td>44</td>
<td>n.d.</td>
<td>0.18</td>
</tr>
<tr>
<td>Ventura River near Ventura (11118500)</td>
<td>487</td>
<td>71</td>
<td>0.90</td>
<td>0.94</td>
</tr>
<tr>
<td>Santa Ynez Mountain Creeks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carpenteria Creek (11119500)</td>
<td>34</td>
<td>60</td>
<td>n.d.</td>
<td>0.057</td>
</tr>
<tr>
<td>Atascadero Creek (11120000)</td>
<td>49</td>
<td>59</td>
<td>n.d.</td>
<td>0.076</td>
</tr>
<tr>
<td>San Jose Creek (11120500)</td>
<td>14.3</td>
<td>58</td>
<td>n.d.</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Note: n.d.—no or insufficient data. LA—Los Angeles.

Castaic Dams of the Santa Clara River watersheds and the Casitas and Matillija Dams of the Ventura River watersheds.

Fine-Sediment Sampling and Analyses

Fine-sediment sampling was conducted between 1997 and 2000 at 13 previously unmonitored sites (11 within the Santa Ynez Mountains and one each at the mouths of the Santa Clara and Ventura Rivers; Fig. 5: Table 2) to evaluate the relationships between watershed characteristics and sediment yield. Sediment yield differences were deemed significant if they were greater than the uncertainty in the sampling results, which were large, as shown later. Sites were sampled during and immediately following storms in a west to east direction, which followed typical storm progression across the region of 15–35 km/h (Warrick, 2002). If it was still raining after a complete sampling of all sites, sampling was continued until storm conditions subsided.

An important consideration of this sampling program was that standard wading-rod or bridge-mounted sampling techniques were much too dangerous in the high flood flows within the boulder-lined channels (surface current velocities were estimated to be 2–5 m/s during floods). Thus, our river sampling technique consisted of grab sampling the surface water in triplicate from the thalweg of each creek. These techniques will certainly provide underestimations of total suspended-sediment concentrations and especially the coarsest grain-size fraction—as addressed later—but we note that traditional sampling techniques are not generally attempted in these stream settings (Guy and Norman, 1970). Thus, we henceforth describe our samples as “fine sediment” owing to the likelihood of underestimation of the coarsest fraction.

Laboratory techniques consisted of filtering samples on preweighed Millipore AP40 GFF filters (~0.4 mm pore size), which were oven-dried, desiccated for 24 h, and reweighed. Our samples from high flooding were commonly >10%–20% sand (data provided in the GSA Data Repository [see footnote 1]), which is consistent with the sand content from the USGS suspended-sediment samples of the creeks and rivers in the region (cf. Willis and Griggs, 2003). All triplicate samples had standard errors of <15%.

Flow rates for the sites were not measured directly due to safety concerns. Therefore, 10 USGS river gauges within the study area (Fig. 5B) were used to calculate a uniform specific discharge during each sampling interval. This was calculated by normalizing each discharge record by drainage area, finding and applying the linear rate of storm progression across the study area, and solving for discharge for each sample’s time and location. The 95% confidence levels of these specific discharge values were all less than 60% and commonly less than 40%. For comparisons across the watersheds, discharge estimates were normalized to mean annual peak flooding rates (Qmax), which was assessed at the 2.33 yr recurrence interval (p = 0.429), found to be 0.64 m/s/km² (equivalent to 0.64 mm/s) from the 11 USGS gages, and had variance unrelated to drainage basin size.

Total uncertainty in these fine-sediment sampling results were at most 75% and commonly less than 55%. Differences in excess of this uncertainty were deemed significant. To make these comparisons across the watersheds, fine-sediment concentration and river discharge data were fit with the LOWESS techniques detailed already.

### Table 2: Fine-Sediment Sampling Sites

<table>
<thead>
<tr>
<th>Station number</th>
<th>Station name</th>
<th>Sampling location</th>
<th>Drainage area (km²)</th>
<th>No. of suspended sediment samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gaviota Creek</td>
<td>Hollister Ranch Road</td>
<td>52.2</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>San Onofre Creek</td>
<td>Creek mouth</td>
<td>5.3</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Refugio Creek</td>
<td>State Park campground bridge</td>
<td>21.2</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>El Capitan Creek</td>
<td>State Park Road bridge</td>
<td>16.0</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>Atascadero Creek</td>
<td>Patterson Ave.*</td>
<td>49.0</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>Monteucito Creek</td>
<td>Footbridge at mouth</td>
<td>17.0</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>Santa Monica Creek</td>
<td>Carpinteria Ave. bridge</td>
<td>9.3</td>
<td>12</td>
</tr>
<tr>
<td>8</td>
<td>Franklin Creek</td>
<td>7th Ave. bridge</td>
<td>9.8</td>
<td>12</td>
</tr>
<tr>
<td>9</td>
<td>Rincon Creek</td>
<td>Highway 101 culvert</td>
<td>39.0</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>Willow Creek</td>
<td>Hobson Road bridge</td>
<td>13.4</td>
<td>11</td>
</tr>
<tr>
<td>11</td>
<td>Padre Juan Creek</td>
<td>Hobson Road culvert</td>
<td>7.8</td>
<td>8</td>
</tr>
<tr>
<td>12</td>
<td>Ventura River</td>
<td>Main Street bridge</td>
<td>580</td>
<td>13</td>
</tr>
<tr>
<td>13</td>
<td>Santa Clara River</td>
<td>Harbor Boulevard bridge</td>
<td>4210</td>
<td>14</td>
</tr>
</tbody>
</table>

*Site is located at U.S. Geological Survey station 11120000.*
Statistical Correlation Methods

Stepwise, multiple variable linear correlation analyses (Graybill and Iyer, 1994) were conducted to determine the watershed factors with greatest significance to the water and sediment discharge results. Watershed characteristics were not combined if they were collinear ($r^2 > 0.8$ for linear regression; Montgomery and Peck, 1992), and thus not independent, owing to the high likelihood of misleading inferences. A cross-correlation matrix is provided in the GSA Data Repository (see footnote 1). For all analyses, F-statistics and t-statistics ($p < 0.05$) were used to determine if the regression relationships occurred by chance and how significant each characteristic was to the regression equation. Results are presented here for both the first step of these regression analyses (i.e., single variable regression results) and the final step (complete stepwise, multiple variable regression).

The watershed characteristics used for statistical analyses focused on four potential controls of water and sediment yield: precipitation, hydrography, lithology, and land use. A complete tabulation of these data is included in the GSA Data Repository (see footnote 1). For each characteristic, watershed boundaries were superimposed onto data sets, which were analyzed for percent coverage.

Average annual precipitation was evaluated by the mean 1960–2000 rainfall climatology of Spatial Climate Analysis Service (2000) with an accuracy of 10 cm (Fig. 2). Watershed hydrography was evaluated with USGS 1:24,000 digital elevation models (DEM, with horizontal resolution of 30 m) and analyzed with the RiverTools (version 2.4) computer application. Hydrographic measures (including watershed area, maximum elevation, total relief, and along-channel slope) were obtained for the entire watershed and for the Horton-ordered subwatersheds within each watershed. The bedrock lithology of the Santa Ynez Mountain portion of the study area has been mapped at 1:24,000 scale (Dibblee Geological Foundation, 2008). For the remainder of the study area (including the Ventura and Santa Clara River basins), bedrock lithology was assessed with a 1:250,000 geologic map (Saucedo et al., 2000), which is summarized in Figure 2.

Land use was assessed with the Geographical Approach to Planning for Biological Diversity (GAP; Davis et al., 1998) analysis of mainland California, which was summarized into five main types: chaparral/woodland, grassland, agriculture, urban, and barren, which includes bedrock outcrops, nonagricultural clearings, gullied lands, and landslide scars. An example of barren areas in the study area is shown in Figure 6. An assessment of the GAP data was made by an independent interpretation of land use from analyses of 1:24,000 USGS orthophotoquads (USGS, 1980) for the watersheds of fine-sediment sampling sites 1–11. Area-based classification error ranged from 3% for chaparral/woodland to 16% for urban, with a spatial average of 10% across all five land uses.

Statistical analyses were completed using percent coverage of lithologic and land-use types, mean values of the precipitation and hydrographic measures, and mean values of water yield, sediment yield, and fine-sediment concentrations. We assessed the impact of measurement uncertainty on these results by also conducting the statistical analyses with extreme values of the uncertainty for sediment and water yields. Some of the indices were combined to represent broader characteristic patterns within the drainage basins. Lithologic characteristics were combined to produce groups of common

Figure 6. Examples of barren landscape within Quaternary/Pliocene marine formations of a small coastal watershed in the study area. Barren areas are represented by bedrock outcrops, gully complexes, landslides, and oil well pads and roads. (A) Vertical perspective with drainage divide (red dashed line) and oblique image perspectives (yellow arrows); (B–C) oblique perspectives with no vertical exaggeration. Image was obtained from Google Earth on 15 February 2008.
RESULTS

Water and Sediment Yields and Budgets

Discharge from the study-area watersheds is dominated by winter precipitation, which produces brief pulses of water and sediment. Over 50% of the annual water discharge and over 90% of the sediment discharge occur on average during < 1% of the time in each year. Water and sediment discharge from the study-area watersheds also varies substantially year-to-year. For example, annual suspended-sediment discharge from the Santa Clara River varies by several orders of magnitude, and the 1969–1999 mean (6.8 Mt/yr) can be surpassed by almost an order of magnitude during extremely wet winters such as 1969 (Fig. 7). Further, half of the total sediment discharge is delivered during only 10% of the total years (i.e., 3 of the 31 yr record; Fig. 7).

Although there is considerable variability in annual sediment flux, year-to-year comparisons of sediment flux from study area basins produce remarkably consistent relationships. For example, suspended-sediment discharge from the Sespe and Ventura Rivers are shown in Figure 8, for which a linear regression explains 94% of the variability in the data. This pattern is consistent for much of the remaining study area, as median and mean correlation coefficients for such linear regressions are 0.91 and 0.86, respectively (Table 3). Correlation coefficients are generally highest for adjacent basins, and this high correlation is likely due to similar responses to the broad frontal storm systems that cause rainfall in the Western Transverse Ranges.

The high correlation in annual sediment fluxes is important for two reasons. First, it allows us to extend the sediment-discharge calculations across short gaps in time in the stream gauge data, as noted previously and presented in Figure 7. Secondly, although average annual rates may not represent the magnitude and variation of flux during the range of winter storm conditions (e.g., Fig. 7), average rates do represent the consistent variation across the study area over these conditions. Thus, the basin-to-basin variability in average flux rates presented here can be understood to be consistent with the variability inherent during a wide range of winter conditions for the years observed.

Integration of the sediment discharge results into suspended-sediment discharge budgets for 1969–1999 revealed significant differences in sediment yields. Mean sediment yield was computed to range between 740 and 5300 t/km²/yr (Fig. 9A). These rates are lowest in the inland portions of the Santa Clara River basin (740–1600 t/km²/yr) and highest in the final portion of the Santa Clara River basin (5300 t/km²/yr), although this highest rate was computed by mass balance and thus has higher uncertainty, as discussed later. Basins within the Ventura River watershed have rates of ~2500 t/km²/yr (Fig. 9A), which are consistent with the rates of sediment transport from Sespe and Hopper Creeks of the Santa Clara River (2300–2700 t/km²/yr). Although sediment yield could be computed for a majority of the study area, it is important to note that certain areas, such as the lowest portion of the Ventura River watershed and the entire Santa Ynez Mountain drainages, have limited or no USGS data to evaluate sediment discharge (Fig. 9A).

Considerable variation also exists in the average water discharge rates for 1969–1999 (Fig. 9B). The highest rates of water discharge are in excess of 30 cm/yr and occur in headland tributaries of the Ventura River (both forks of Matillija Creek) and the Santa Paula Creek drainage of the Santa Clara River. Sespe Creek, which provides the greatest source of water in the Santa Clara River, produces water at a relatively high rate of 23 cm/yr. Much lower rates of water yield were calculated in the inland and lower basins of the Santa Clara River, 3.8–7.8 cm/yr (Fig. 9B). The Santa Ynez Mountain drainages generally had moderate rates of runoff, ranging from 15 to 18 cm/yr.

The discharge-weighted suspended-sediment concentration from each basin was calculated as the quotient of the sediment and water yields and ranged from 8 to 35 g/L (Fig. 9C). Although these concentrations are very high compared to many large rivers of the world, they are not unusual for small, steep basins in semiarid or Mediterranean climates (e.g., Milliman and Syvitski, 1992; Mulder and Syvitski, 1995). The lower portion of the Santa Clara River watershed was computed to have the highest suspended-sediment concentration for the study area, with a mean concentration of 35 g/L (Fig. 9C).

Integrated discharge budgets for the Santa Clara River clearly reveal the variation of the water and suspended-sediment results (Fig. 10). The suspended-sediment budget shows that the majority (58%) of the sediment discharged at the mouth is generated in the combined Lower and Santa Paula portions of the basin (Fig. 10A). The uncertainty in the sediment flux from this portion of the Santa Clara River was calculated by assuming independent, random errors in the mass balance, which resulted in ±2.0 Mt/yr. The extremes of this uncertainty suggest that the combined Lower and Santa Paula tributaries either contribute sediment consistent with the next highest rates within the study area (i.e., 2600 t/km²/yr) or at rates approximately three times these rates (i.e., 7900 t/km²/yr). In contrast, the Santa Clara River water budget shows that the greatest portion (44%; uncertainty range = 32%–59%) of water discharging at the river mouth originates from Sespe Creek (Fig. 10B). Hence, even with the uncertainty in the observations, the water and sediment budgets of the Santa Clara River watershed suggest that the primary source regions of these materials are not the same.
TABLE 3. CORRELATION COEFFICIENTS (r) OF LINEAR REGRESSION BETWEEN COINCIDENTAL SUSPENDED-SEDIMENT DISCHARGE CALCULATIONS AT U.S. GEOLOGICAL SURVEY GAUGES FOR WATER YEARS 1969–1999

<table>
<thead>
<tr>
<th>Ventura River (11118500)</th>
<th>San Antonio Creek (11117900)</th>
<th>Santa Clara River–Montalvo (11114000)</th>
<th>Sespe Creek (11113000)</th>
<th>Hopper Creek (11111050)</th>
<th>Santa Clara River–LA county line (11108500)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Antonio Creek (11117500)</td>
<td>0.84</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Santa Clara River–Montalvo (11113920)</td>
<td>0.83</td>
<td>0.94</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Sespe Creek (11113000)</td>
<td>0.94</td>
<td>0.94</td>
<td>0.96</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Hopper Creek (11110500)</td>
<td>0.88</td>
<td>0.91</td>
<td>0.97</td>
<td>0.92</td>
<td>na</td>
</tr>
<tr>
<td>Santa Clara River–LA county line (11108500)</td>
<td>0.56</td>
<td>0.91</td>
<td>0.81</td>
<td>0.67</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Note: Gauges are listed in geographic order from west to east. LA—Los Angeles.

Median r² of all regressions = 0.91

Mean r² of all regressions = 0.86

Figure 9. Average sediment yield, water yield, and discharge-weighted sediment concentration during 1969–1999 for the study area watersheds with U.S. Geological Survey (USGS) sampling. Sediment concentration is computed as the quotient of A and B.
Correlation Analyses: Sediment and Water Yields

The results presented here were compared with watershed characteristics of each basin and resulted in a number of statistically significantly correlations (Table 4). In a single-variable regression, suspended-sediment yield correlated significantly with land use and lithologic variables (Table 4A). Human-altered land uses (agriculture and grassland) were consistently positively correlated with sediment yield ($r^2 = 0.46–0.75$), while chaparral/woodland was inversely related with sediment yield ($r^2 = 0.46$). Quaternary to Pliocene marine sedimentary bedrock also correlated with sediment yield and explained roughly half of the variance (Table 4A).

Correlation analyses for water discharge produced very different results than those for sediment yield (Table 4B). As might be expected, average annual precipitation exhibited strong correlation and a positive relation ($r^2 = 0.78$), but correlation was also found within the Eocene marine sedimentary formations ($r^2 = 0.82$), which are dominantly sandstones that make up the steep crests of the region’s mountains (Fig. 2). Other significant single-variable correlations include two measures of the region’s hydrography, upland relief and slope, and total granitic and metamorphic bedrock (Table 4B).

The correlation results for discharge-weighted suspended-sediment concentrations were consistent with analyses for sediment and water yields, and significant variables included Eocene marine sedimentary formations, Quaternary/Pliocene marine sedimentary formations, and total agriculture, grassland, and barren land use ($r^2 = 0.46–51$; Table 4C).

Using standard stepwise correlation techniques, additional watershed characteristics were included with those that were shown to have first-order effects to test for correlation significance. Few of these multiple-variable correlations, however, provided statistically significant results ($p < 0.05$) that explained a greater portion of the data variability than the best single-variable correlations. Exceptions to this occurred for sediment yield and sediment concentration (Table 5). For sediment yield, the Quaternary/Pliocene marine formations consistently provided significant correlations with the following secondary variables: drainage area ($r^2 = 0.88$), total granitic and metamorphic bedrock ($r^2 = 0.76–0.82$), and precipitation ($r^2 = 0.76$; Table 5). Agriculture and grassland also provided significant correlations with the slope of the first-order watersheds ($r^2 = 0.86$). The sediment concentration correlations were also improved with multivariable regressions (Table 5C), showing the potential secondary

---

**Figure 10.** Average annual suspended-sediment and water budgets for the Santa Clara River watershed for 1969–1999. Inset shows a map of the tributary drainage areas.
influences of agriculture, agriculture and grassland, Quaternary/Pliocene marine formations, chaparral, and average annual precipitation.

We also assessed the impact of calculation uncertainty on these results by conducting the statistical analyses using the uncertainty extremes of the sediment and water yields. Although different correlation equations and coefficients were found, the patterns in these results were very similar to those described already. For example, water yield consistently correlated best with precipitation, the Eocene marine sedimentary formations, and watershed relief and slope. Sediment yield was similarly found to correlate positively with the Quaternary/Pliocene marine sedimentary formations, grassland and agricultural land use, and watershed slope; it correlated negatively with igneous and metamorphic formations.

**Fine-Sediment Sampling**

The results from the 11 Santa Ynez Mountain creeks (Fig. 11) provide another opportunity to evaluate the variability across these similarly sized and previously unmonitored basins. Most of the Santa Ynez Mountain creek sites were sampled at a wide range of discharge rates, with maximum discharges in excess of $2 \times Q_{\text{mean}}$ (>5 yr recurrence intervals). Unfortunately, sites 10 and 11 could not be sampled during the largest runoff events because landslides and debris flows had closed access roads to these sites. Fine-sediment concentrations were often very high (>10 g/L) and positively correlated with discharge (Fig. 11). Further, consistent hysteresis relationships with respect to rising and falling limbs of the hydrographs were not observed at any site.

Fine-sediment concentrations at equivalent runoff rates showed order-of-magnitude differences in the raw concentration data and fitted LOWESS relationships between sites (Fig. 12). For example, concentrations at Padre Juan Creek (site 11) were commonly an order of magnitude greater than most of the other creeks (Fig. 12). The variation in the fine-sediment sampling results are shown geographically with mapped sediment concentrations of the mean annual flood ($Q_{\text{mean}}$), intervals, where concentrations were interpreted from the best-fit LOWESS lines (Fig. 13). These patterns show that elevated concentrations were consistently observed in the three eastern watersheds (sites 9–11) for all flow rates and Gaviota Creek (site 1) at higher flow rates. For the remaining central basins (sites 2–8), fine-sediment concentrations are all within an order of magnitude for each flow rate (Fig. 13).

**Correlation Analyses: Fine-Sediment Sampling**

Because the differences in fine-sediment concentration patterns for the Santa Ynez Mountains (orders of magnitude) were in excess of the uncertainty of these measurements (less than 75%), we evaluated the statistical relationships between these and watershed variables. Examples of some of these watershed variables are included in Figure 14, which reveals substantial differences in lithologic, land use, and hydrographic characteristics.

A number of these characteristics were significantly correlated with the fine-sediment results as assessed by the LOWESS relationships, and these correlations were generally better for the higher discharge compared to lower discharge rates (Table 6). Fine-sediment concentrations were most commonly correlated with lithologic characteristics, such as Quaternary/Pliocene marine formations, percent landslides, Eocene marine formations, and total sandstone bedrock (Table 6). Barren land use also showed strong correlations with fine-sediment concentrations (Table 6).

All significant stepwise multiple-variable regressions that provided better correlation than single-variable regressions are shown in Table 7. We note that all but one of the multiple-variable regressions have a lithologic characteristic in the final regression equation. These lithologic characteristics include Quaternary/Pliocene marine formations and percent landslides. Other characteristics that were significantly correlated include: percent barren land use (two occurrences, positive slope), maximum elevation (two occurrences, positive slope), drainage area (four occurrences, positive slope), and grassland (three occurrences, mixed slopes; Table 7). We note that Quaternary/Pliocene marine and barren land use could not be combined owing to high collinearity.

**DISCUSSION**

These results show that sediment yield is variable in the drainages of the Western Transverse Ranges and consistently correlated with land use and lithologic characteristics of the watersheds. Here, we compare the results from the two methods and examine the watershed characteristics to evaluate why they may influence sediment budgets.

**Result Comparisons**

Two different data sources were evaluated, and it is valuable here to discuss how these results can be compared. The regional analyses produced sediment and water mass balances, whereas the fine-sediment sampling characterized concentrations at a series of uniform discharge rates, which may or may not be interrelated as suggested by Syvitski et al. (2000) and Warrick and Rubin (2007).

It is therefore important to assess whether the fine-sediment concentration results were influenced by nonuniform rates of water discharge. Although water discharge in the Santa Ynez Mountain streams is consistent over scales ranging from single hydrologic events to decades, exceptions exist, including San Jose Creek (USGS 11120500; ~130% of regional mean) and Franklin Creek (USGS 11119530; ~60% of regional mean). These different rates of discharge appear to be related to orographic effects on precipitation and differences in drainage-basin elevation. San Jose Creek drains a higher-elevation basin (mean precipitation = 60 cm/yr), and Franklin Creek drains a lower-elevation basin (mean precipitation = 40 cm/yr).
Figure 11. Suspended-sediment sampling results from the 11 Santa Ynez Mountain drainages. Discharge has been normalized by the mean annual flood (maf) as described in the text.

Figure 12. Comparison of suspended-sediment sampling results from three Santa Ynez Mountain streams with order-of-magnitude differences in sediment concentrations.
It is important to note here that the two eastern sampling sites (sites 10 and 11) also have a lower average annual precipitation (40 cm/yr), which may suggest that their elevated sediment concentrations (Figs. 12 and 13) may, in part, be due to lower water discharge. However, assuming that the water discharge from these basins is 60% of the average rate of Santa Ynez Mountain creeks (consistent with Franklin Creek), average sediment concentrations would be elevated by ~170% using the theory of Warrick and Rubin (2007). Including this correction, the average concentrations from sites 10 and 11, and thus their sediment yield, would still be substantially greater—at least five-times—than the central basins of the Santa Ynez Mountains (sites 2–8).

This suggests that the differences in sediment concentrations among the Santa Ynez Mountain creeks are much more related to variations in sediment yield rather than water discharge.

It is also relevant to compare the results of the two correlation analyses (Tables 4–7). The results of both analyses were similar in that lithologic and land-use variables were consistently found to be most significant and result in similar patterns. Thus, although the two data series had different methods of observation and geographic and spatial scales, the youngest marine sedimentary bedrock and barren or human-modified land uses were consistently correlated with sediment yield. Next, we examine these variables in further detail.

### Lithologic Relations

The most consistent lithologic correlations for sediment yields were with Quaternary/Pliocene marine sedimentary formations. Mass-wasting processes of many scales (from shallow debris flows to large landslides) are observed throughout these formations (Figs. 6 and 14). Putnam (1942 p. 727–728) described the Pico Formation, which is the dominant Quaternary/Pliocene marine formation of the study area, writing “nearly every square foot of surface on hillslopes underlain by upper Pico clay shale is in motion downslope, or has moved in the very recent geologic past.” The very large La Conchita landslides occurred within this region following the wet...
Sediment yield in California

winters of 1995 and 2005 (Jibson, 2005), while smaller landslides and debris flows are common throughout this landscape (Stock et al., 2006). Further, as noted already, the authors could not sample sites 10 and 11, which lie almost wholly in Quaternary/Pliocene marine formations, during the largest storms due to road closures from landslides and debris flows.

Mass wasting of this scale certainly influences sediment fluxes from these drainages, such as has been shown for mountainous drainages of New Zealand and Taiwan (Hovius et al., 1997; Fuller et al., 2003). The weakly consolidated Quaternary/Pliocene marine sedimentary rocks of the Western Transverse Range also coincide with the region of greatest reported uplift (>5 mm/yr; Fig. 2) and are highly correlated with barren land use ($r = 0.93$), which should result in exceptional erosion rates. Thus, the first-order correlations between sediment discharge and Quaternary/Pliocene marine formations are consistent with landscape mass-wasting processes observed by others.

These findings are further supported with a comparison of suspended-sediment data from the Ventura River (Fig. 15). Comparison of these data is important because the USGS station is located immediately upstream of a region of Quaternary/Pliocene marine formations, while our river mouth site lies immediately downstream of this region (Fig. 15A). Fine-sediment concentrations at the river mouth are consistently higher than suspended-sediment concentrations measured upstream at the USGS station (Fig. 15B), all river mouth samples were greater than the LOWESS rating curve for the USGS station, and 8 of the 13 samples (62%) were greater than one standard error above this curve (Fig. 15B). This difference is noteworthy because the fine-sediment samples should preferentially produce lower concentration results than the depth-integrated USGS samples. This result cannot be attributed to unusually high sediment yields triggered by exceptional precipitation during our sampling, because the USGS samples (1969–1999, $n = 199$) include those taken concurrent with our program and during years with substantially greater precipitation (e.g., 1969 and 1978). Below we show that the actual sediment load of the entire Ventura River watershed is

![Figure 14](https://example.com/figure14.png)

**Figure 14.** Select drainage basin characteristics for the 11 fine-sediment sampling sites within the Santa Ynez Mountain creeks. Land uses in F include: 1—combined chaparral and woodland, 2—barren, 3—grassland, 4—agriculture, 5—urban.

<table>
<thead>
<tr>
<th>Watershed variable</th>
<th>Type of variable</th>
<th>2.0 $\times Q_{\text{maf}}$ slope</th>
<th>1.0 $\times Q_{\text{maf}}$ slope</th>
<th>0.5 $\times Q_{\text{maf}}$ slope</th>
<th>0.2 $\times Q_{\text{maf}}$ slope</th>
<th>0.1 $\times Q_{\text{maf}}$ slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary/Pliocene marine formations</td>
<td>G</td>
<td>0.94 +     0.87 +    +    0.87 +</td>
<td>0.71 +</td>
<td>0.71 +</td>
<td>0.84 +</td>
<td></td>
</tr>
<tr>
<td>Barren</td>
<td>LU</td>
<td>0.92 +     +     0.82 +     +     0.73 +</td>
<td>+ 0.51 +</td>
<td>+ 0.68 +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landslides</td>
<td>G</td>
<td>0.82 +     +     0.82 +     +     0.78 +</td>
<td>+ 0.63 +</td>
<td>+ 0.74 +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eocene marine formations</td>
<td>G</td>
<td>0.45 –     0.45 –     0.46 –</td>
<td>– 0.39 –</td>
<td>– 0.37 –</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Total sandstone</td>
<td>G</td>
<td>0.42 –     0.45 –     0.43 –</td>
<td>– 0.37 –</td>
<td>– 0.36 –</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Ave. annual precipitation</td>
<td>P</td>
<td>0.45 –     0.37 –     –</td>
<td>– not significant</td>
<td>– not significant</td>
<td>– not significant</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Data are ranked according to average correlation. Statistical significance assessed at $p < 0.05$. G—geologic; LU—land use; P—precipitation.
substantially underestimated due to this upstream sampling bias of the USGS gauge.

We also note the Eocene marine formations, which are dominated by sandstones, are inversely related to sediment concentrations (Tables 4–7). These formations are found solely in the region’s highest peaks and drainage divides (Fig. 2) and also correlate significantly with water discharge (Table 4) owing to orographic effects on precipitation. The higher rates of runoff may contribute to lower concentrations due to dilution, as noted previously, especially because they do not correlate with measurements of sediment yield (Tables 4–5). In contrast, the granitic and metamorphic formations appear to be eroding at the lowest rates of the study area, as evidenced by their lower sediment yields (Fig. 9A) and second-order statistical relations with sediment yield (Table 5).

Land-Use Relations

Work within the Western Transverse Ranges by Cole and Liu (1994), Gabet and Dunne (2002), and Pinter and Vestal (2005) suggests that denudation rates are higher under grasslands, which are ubiquitously nonnative species, than under native chaparral. Thus, it would be expected for areas of grasslands to correlate with sediment-discharge measurements from our study area (Tables 4 and 5). The fine-sediment sampling results provide a mixed assessment of land-use effects because grassland is a second-order variable with both positive and inverse correlations (Table 7). Barren land use was much more consistently correlated as a first- and second-order variable with the fine-sediment results (Tables 6 and 7), although we note that it is highly collinear with Quaternary/Pliocene marine formations ($r = 0.93$).

Other Relations

A number of other watershed characteristics were found to be statistically significantly related to measures of sediment discharge. For example, drainage-basin area was both positively and negatively correlated with sediment discharge as a second-order effect (Tables 5 and 7). Drainage area is generally found to be inversely related to sediment yield of a watershed (e.g., Milliman and Syvitski, 1992), and we can provide no physical evidence for our results. Other watershed characteristics that were significant appear to follow classic sediment-yield patterns. First-order slope was positively correlated with sediment discharge as a second-order effect (Table 5), and this reflects the steepness of the upper drainage basin, which is commonly related to sediment yield (e.g., Milliman and Syvitski, 1992).

INTEGRATION AND CONCLUSION

Sampling results suggest that sediment discharge is both high compared to regional and global averages and considerably variable in the drainages of the Western Transverse Range of California. Lithologic and land-use characteristics were found to be most important to inferred rates of sediment yield. Regions with considerable areas of young bedrock (Quaternary/Pliocene marine) and human-altered land uses were found to discharge the highest rates and concentrations of sediment. Analyses of the Ventura River suggest that the presence of Quaternary/Pliocene marine formations significantly increased sediment discharge downstream (Fig. 15). These increases in sediment yield are on the order of fivefold within spatial scales of 10 km.

The location of the highest sediment yield in the Santa Ynez Mountains is the easternmost drainages (Fig. 13), an area that has only about half of the average relief of the remaining range (Fig. 14B) and is suggested to have the greatest rates of uplift within the Western Transverse Range (Fig. 2). Using only this relief and uplift information, simple geomorphologic theory (e.g., Burbank and Anderson, 2000) would suggest that these drainages must be both easily erodible and have high rates of sediment discharge, both of which have been shown here.

Many watershed characteristics were not significantly correlated with sediment discharge, including debris basins and urban land uses. This does not suggest that they have no influence on erosion and sediment discharge in the region. On the contrary, these factors may have very significant effects on sediment yield (cf. Trimble, 1997; Warrick and Rubin, 2007); however, they were not found to have principal first- or second-order effects across the entire Western Transverse Range. We note that particle-size analyses of sediment deposited in the 19 major debris basins of the Santa Ynez Mountains reveal that 80%–95% is sand and gravel (>75 mm; K. Treiburg, 2000, personal commun., Santa Barbara County Flood Control). An estimated 1.5 Mm$^3$ of this material was artificially removed from debris basins between 1969 and 1999 and placed on fallow lands or landfilled (Warrick, 2002). Thus, the debris basins likely reduce sand delivery to the coast but have little effect on the majority of sediment discharge, which is ~80% fine sediment.

Finally, the high variability in sediment yields (at least fivefold) within very small spatial scales (~10 km) shows that sediment yields cannot be assumed to be uniform for regions within the Western Transverse Range. This variability would be overlooked using classic first-order approximations. For example, assessment of

<table>
<thead>
<tr>
<th>Regression coefficient (slope)</th>
<th>Variable</th>
<th>Type of variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \times Q_{maf}$</td>
<td>Quaternary/Pliocene marine (+)</td>
<td>G</td>
<td>0.89</td>
</tr>
<tr>
<td>$0.5 \times Q_{maf}$</td>
<td>Grassland (#)</td>
<td>G</td>
<td>0.95</td>
</tr>
<tr>
<td>$0.2 \times Q_{maf}$</td>
<td>Area (+)</td>
<td>G</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Max. elevation (#)</td>
<td>G</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Note: Results are only presented if they both are significant ($p < 0.05$) and produce correlations better than the best of the single-variable regressions (see Table 6).
denudation based largely on relief or slope (e.g., Milliman and Syvitski, 1992; Syvitski et al., 2000) would have grossly underestimated sediment yield in portions of the Western Transverse Range. To illustrate this, we turn to the Ventura River (Fig. 15). A conservative assumption from our results is that sediment yield for the unmonitored portion of this watershed is double that of the monitored watershed, which would result in a total sediment flux during 1969–1999 of 1.5 Mt/yr, which is 62% higher than that estimated from the Ventura River gauging station (Table 1). We note that previous inventories of Southern California sediment flux (e.g., Brownlie and Taylor, 1981) have not included additional sediment yield from the unmonitored portions of the rivers due to low relief and relatively small drainage sizes. These previous estimates are likely underestimated for the Ventura River by at least 50% due to the high sediment yield of the unmonitored area.

We suggest that exceptional care must be taken when attempting to extend sediment discharge results from one drainage (or region) to another using techniques such as uniform sediment yield or transferred sediment rating curves (e.g., Brownlie and Taylor, 1981; Schwallbach and Gorsline, 1985; Willis and Griggs, 2003), because slight changes in landscape features or processes may dramatically influence denudation. Simple process-based evaluation of landscape denudation (e.g., Reid and Dunne, 1996; Fuller et al., 2003) may assist in eliminating these errors.

In conclusion, sediment yield within the Western Transverse Ranges varies by an order of magnitude over scales of 10–100 km. These rates of sediment yield were significantly correlated to drainage basin properties, especially lithology and land use. The high rates of denudation in the Western Transverse Ranges can be attributed, in part, to localized areas with exceptional rates of erosion. This reinforces the need for process-based sediment budgets and suggests that caution should be used when transferring sediment yield or sediment rating curves.

ACKNOWLEDGMENTS

This paper is dedicated to the family, friends, and students of Leal A.K. Mertes—may she continue to inspire us all. We would like to thank Scott Valentine and Sherie L'Heureux for assistance with sample collection and analyses. Murray Hicks and an anonymous reviewer provided constructive comments that improved the paper. We also thank Tom Dunne, John Milliman, Bob Meade, Amy Draut, and Patrick Barnard for helpful discussions and comments. Funding and support for this work was provided by a National Aeronautics and Space Administration (NASA) Earth System Science Fellowship, a U.S. Geological Survey (USGS) Mendenhall Postdoc Fellowship, the National Science Foundation (NSF) Santa Barbara Coastal Long Term Ecological Research, and USGS Coastal and Marine Geology Program funds.

REFERENCES CITED


