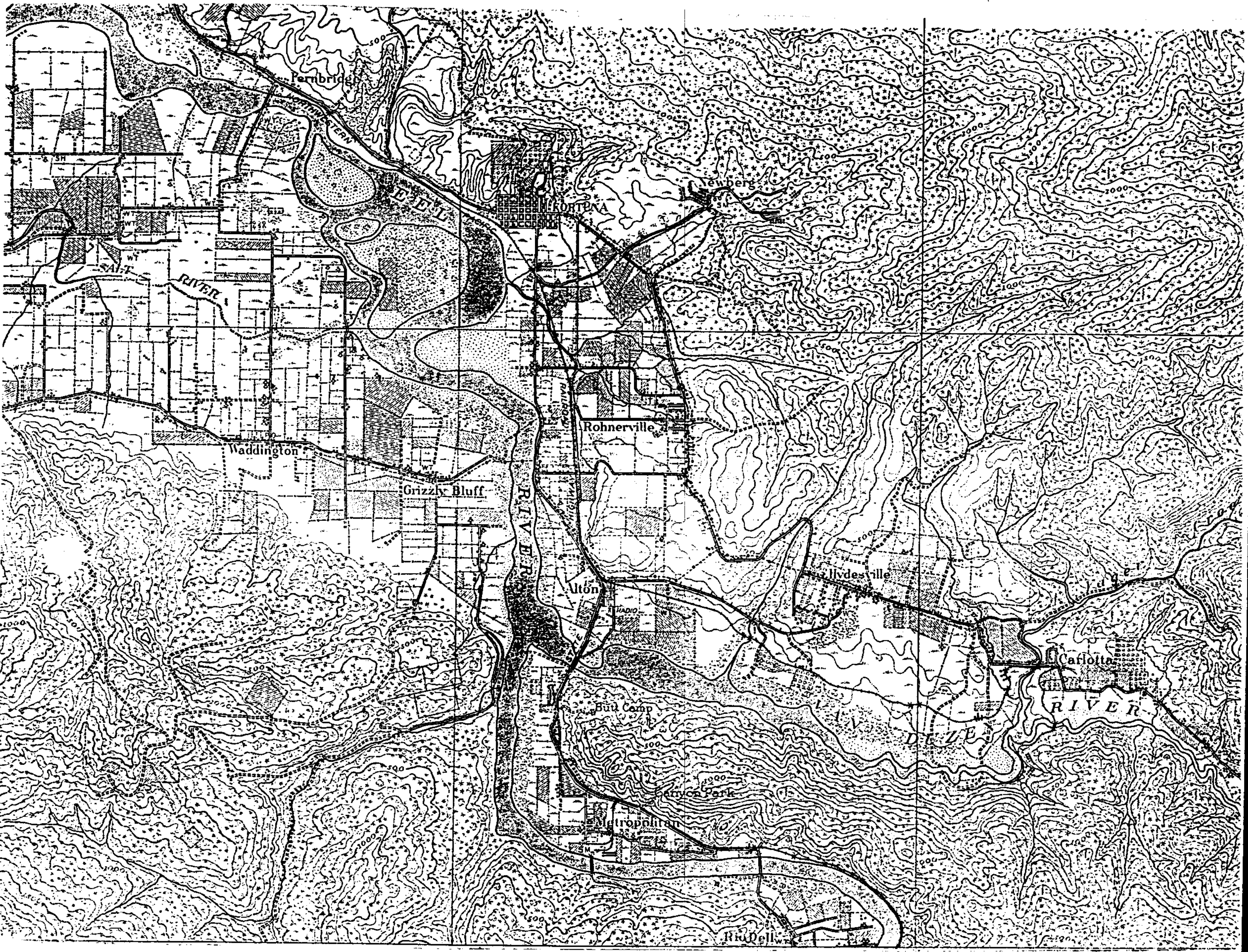
Appendix B

G. Mathias Kondolf

Consultants Report

AGGREGATE EXTRACTION FROM THE EEL AND MAD RIVERS, HUMBOLDT COUNTY:

GEOMORPHIC AND ENVIRONMENTAL PLANNING CONSIDERATIONS



by
G. Mathias Kondolf, Ph.D.
2241 Ward Street
Berkeley CA 94705

5 April 1993

AGGREGATE EXTRACTION FROM THE EEL AND MAD RIVERS, HUMBOLDT COUNTY: GEOMORPHIC AND ENVIRONMENTAL PLANNING CONSIDERATIONS

by
G. Mathias Kondolf, Ph.D.
2241 Ward Street
Berkeley CA 94705

a report submitted to the
Planning Department, County of Humboldt
3015 H Street
Eureka CA 95501

5 April 1993

:MAD.4

TABLE OF CONTENTS

CONCLUSIONS AND RECOMMENDATIONS

1) By interrupting the continuity of sediment transport through the river system, instream gravel extraction can induce incision and other morphological changes, which can propagate miles upstream and downstream of gravel pits. Incision can occur both downstream and upstream of the gravel pit: downstream due to deprivation of sediment load, upstream from knickpoint migration.

2) The complexity of sediment transport and channel change in natural rivers is such that prediction of river behavior is plagued with a significant degree of uncertainty.

3) Computer models of sediment transport are simplifications of complex natural processes. The National Research Council (1983) concluded that the performance of all such models was so poor that their use could not be justified in flood insurance studies.

4) A thorough historical study of channel change and a sediment budget analysis should be undertaken on the Mad and Eel Rivers as a basis for understanding and predicting impacts in these channels.

5) Changes in river channel form and bed elevation should be monitored using cross sections surveyed to a common datum using standard procedures. Cross sections should be surveyed not only in extraction areas but in intervening reaches as well to provide longitudinal continuity.

6) The County should consider establishment of minimum thalweg elevations (redline) to protect bridge crossings and other resources. Incision of the thalweg below the redline would trigger a restriction or halt in extraction and any other activities that could be inducing incision under further studies indicate that extraction can be safely resumed.

7) Upland sources of aggregate (quarry and terrace gravels) should be inventoried and evaluated throughout the region.

8) Based on historical information, sediment budget analysis, and inventory of alternative sources, the County should develop a comprehensive aggregate resource management plan. A key component of the plan should be matching aggregate quality with end use requirements.

9) Although an excellent start has been made with historical and sediment budget studies completed for the EIR, the information base necessary to prepare a comprehensive aggregate resource management plan cannot be developed by June 1, so a preliminary EIR should be prepared to satisfy regulatory requirements this year. The preliminary EIR should describe the studies underway and the process by which a regional aggregate management plan will be developed and an EIR done on it in 1994.

10) The problems related to aggregate management in Humboldt County cannot be solved piecemeal. Comprehensive environmental planning is needed to examine all alternative sources and their environmental impacts, and to develop a coherent strategy to supply the county's aggregate needs while minimizing environmental impacts of extraction.

PURPOSE AND SCOPE

The purpose of this report is to provide guidance concerning geomorphic issues related to extraction of sand and gravel from the active channel beds of the Mad and Eel Rivers. Recommendations include consideration of regional approaches to management of all types of aggregate resources and methods of comparing the environmental impacts associated with extraction of each type. This guidance is presented from the perspective of an outside expert familiar with the geomorphic impacts of instream gravel mining and regulation of the activity in the State of California, the gravel requirements of spawning salmonids, and the geomorphic character of rivers of northern California in general, although not previously knowledgeable about particulars of the Mad and Eel Rivers.

This report is a written version (with citations and technical support) of the presentation made in Eureka on 17 December 1992 to a group composed of staff of the Humboldt County Planning and Public Works Departments, members of the Fish and Game Advisory Commission, staff of California Department of Fish and Game, gravel extractors, the local operators association, members of the Technical Committee, a member of the Board of Supervisors, and representatives of environmental organizations. This report applies principles of geomorphology and environmental planning, along with the author's experience with impacts of instream gravel mining elsewhere, to the situation in Humboldt County. However, specific recommendations of quantities extractable, extraction methods, location, and timing, and detailed protocols for monitoring and assessment of environmental factors in Humboldt County is beyond the scope of this report.

Since the site visit and writing of the draft version of this report, considerable historical and sediment budget analysis have been completed and reported by Andre Lehre, Randy Klein, and others as technical input to the EIR. Although I have not had an opportunity to review this material, it appears that these researchers have already completed some of the studies recommended here, although there are outstanding issues remaining that require further study (Randy Klein, personal communication 1993).

This report is organized as follows. An overview of the problem is followed by a review of river processes relevant to understanding the geomorphic issues related to instream aggregate extraction. The concept of sediment budget construction and the limitations of the existing science are reviewed, followed by a discussion of monitoring and management strategies for in-channel projects. The need for a broader, regional approach to management of aggregate demand and sources is considered, along with recommendations for the near-term strategy for Humboldt County in preparation of an EIR for extraction on the Mad River in 1993.

OVERVIEW OF THE PROBLEM

Sand and gravel are used for a large variety of construction activities including roads and highways (base material and asphalt), pipelines (bedding), septic systems (drain rock in leach fields), and concrete (aggregate mix) for highways and buildings. With the rapid population growth and consequent construction boom in California, the demand for aggregate has been strong. In 1986, the production of sand and gravel in California, primarily derived from river channels and their floodplains was estimated at 128,500,000 tons with an estimated value of nearly $500,000,000 (Sandecki 1989), nearly double the estimated production of 65,000,000 tons in 1955.

In Humboldt County, as in many other counties in the state, most aggregate has been derived from river deposits, both active channel and floodplain. This situation developed over time, with many major existing extractions having grown gradually, without, until recently, being subjected to any environmental analysis, and without a thorough planning process or analysis of cumulative effects. Although sediment budget and historical channel change studies have yet to define linkages between specific management activities and specific impacts, instream gravel extraction is implicated in degradation (downcutting) of the Mad River and consequent undermining of the Highway 299 bridge and impacts to other structures. As a result of these concerns, the County is now taking a serious look at the environmental impacts of instream aggregate extraction, in an attempt to balance the goals of aggregate supply for economic development and environmental quality in the Mad and Eel Rivers.

In California, instream gravel extraction is ineffectively regulated. Under the Surface Mine and Reclamation Act (1976, and amended), all mining operations (upland or in-channel) are required to prepare reclamation plans. The notion of reclamation is suitable for upland quarries, but, as I argue here, it is unsuitable for instream mining. Counties or cities are designated as lead agencies for approving reclamation plans and issuing special use permits or vested rights determinations. In Humboldt County, use permits are required of all mines except those operating before 15 May 1965, which may have vested rights (Sidnie Olson, Planning Department, Humboldt County, personal communication 1993). Instream mining operations must also obtain a Streambed Alteration Agreement from the Department of Fish and Game. In addition, permits for filling of waters of the United States may be required from the US Army Corps of Engineers under Section 404 of the Federal Water Pollution Control Act Amendments of 1972 and/or Section 10 of the Rivers and Harbors Act of 1899.

Despite all these requirements, the cumulative impacts of instream aggregate extraction are rarely thoroughly analyzed in any meaningful way, and an analysis of alternatives (required by the National Environmental Policy Act (NEPA), Section 404 of the Clean Water Act, and the California Environmental Quality Act (CEQA) is rarely performed.

In general, as lead agencies, county planning departments rarely have the resources or staff with expertise needed to properly address the technical issues related to instream extraction. In many counties, little monitoring has been conducted by lead agencies to assess compliance with permit conditions, and even less to document channel conditions as a means of assessing impacts. A survey of 56 county-level lead agencies in California in 1990 showed that only nine had established limits tied to hydrology or channel conditions, and only eleven required channel cross sections or aerial photography to monitor impacts (Kondolf and Matthews, in press). Moreover, county officials may be subject to political pressure or may be influenced by the needs of the county itself to extract aggregate for its operations. In many counties, illegal (unpermitted, non-vested) mines continue to operate.

The existing situation is unlikely to persist because of impacts to structures and aquatic resources. Caltrans is both a consumer of 15 percent of the state's aggregate and victim of bridge undermining by channel incision that may be related to instream mining. Mining (and other activities throughout the watershed) can produce incision that may propagate for miles, affecting distant bridges. About 150 of the state's bridges are critically threatened by scour (Cathy Crossett, Caltrans Structures Div., pers. comm. 1991). With the repair and replacement costs potentially reaching hundreds of millions of dollars, pressure is increasing for control of activities potentially responsible. Likewise, as a result of dramatic declines in anadromous salmon runs over recent decades, recent legislation requiring action to restore salmon runs, and recognition that lack of suitable spawning gravel in sites such as the Sacramento River below Keswick Dam is a major obstacle to restoration of salmon runs, pressure from fishery and environmental groups is increasing for stronger regulation of instream aggregate extraction.

This report reviews principles of river processes relevant to evaluation of impacts of instream aggregate extraction, considers the limitations in the science of sediment transport, and presents arguments for comprehensive environmental planning, in which preservation of natural resources and economic needs are balanced through intelligent, businesslike allocation of resources. This environmental planning should involve an inventory of all potential aggregate sources, evaluation of the relative quality of aggregate, and allocation to various end uses as appropriate, with environmental impacts factored into the cost of instream-produced aggregate.

REVIEW OF RIVER PROCESSES

Role of Rivers in the Landscape

As waters flow from high elevation to sea level, they sculpt the landscape, developing complex channel networks and a variety of stream channel forms. Of the rain that falls on the land surface, over half usually goes back into the atmosphere through evaporation or transpiration by plants. The remainder (a variable fraction, typically about one-third) can run off into the stream network, either running off directly into channels or infiltrating into the groundwater and draining more slowly. Obviously the atmosphere cannot provide more water than it receives indefinitely, and this imbalance is settled by evaporation from the sea. More water evaporates from the ocean surface than falls on it as precipitation. We have already observed that more water falls on the land than evaporates from it, so there is a net transfer of moisture from the sea to land. This is due primarily to the greater availability of water for evaporation on the ocean surface and the greater tendency for precipitation over land from orographic effects.

The land area drained by a given river is termed its <u>drainage basin</u> or <u>watershed</u>, and is separated from adjacent watersheds by topographic high points termed <u>drainage divides</u>. Above any point in a river system, the area over which surface runoff is collected to flow past that point is the <u>drainage area</u>. Drainage basins can be defined at many scales, from large river basins such as the Sacramento River at Sacramento (drainage 23,500 square miles), to its tributary basins such as the Pit River (4,700 square miles) and the North Fork of Battle Creek near Manzanita Lake (6 square miles).

Drainage basins can be viewed as the fundamental landscape units because so many processes occurring upstream in the drainage basin affect downstream reaches, and some processes in downstream reaches may affect upstream reaches. For example, construction of roads in the upper drainage basin may increase rates of erosion and sediment delivery to stream channels, filling downstream channels with sediment, causing the channel to <u>aggrade</u> (build up its bed with sediment), as illustrated along Redwood Creek (Kelsey et al., 1981). If the level of the sea or a lake drops, the channel of a tributary stream immediately upstream may <u>incise</u> or degrade (erode its bed downward), and this incision may propagate upstream for miles or tens of miles, as illustrated along Rush Creek, a tributary to Mono Lake (Stine 1987).

Energy Dissipation and Sediment Transport

Energy is dissipated by rivers in a variety of ways: by transport of sediment, by turbulence from rough, irregular bed and banks, and by energy losses at bends (Figure 1). As water flows from the upper reaches of the watershed downward through the drainage network, some of the potential energy inherent in its elevation at the point of origin goes into energy of motion, with the remaining energy expended upon transport of sediment and dissipated in turbulence. The steeper the channel, the more rapid the rate of energy dissipation (conversion of energy from potential to other forms). Steep channels typically have large rocks on the bed (with greater flow resistance and stability), with most energy losses concentrated in localized drops. These drops may be bedrock or boulder steps in step-pool reaches, or gravel-cobble riffles in pool-riffle reaches.

That rivers possess energy in excess of that required to move water to sea level is reflected in the potential for hydroelectric power generation in steep reaches of Sierra Nevada rivers. Many of these hydroelectric power projects are run-of-the-river, involving no large storage reservoirs, but simply diversion of flow from the channel into smooth canals or tunnels that convey the water at a gentle grade along the mountainside above the river. The river falls more steeply (dissipating energy in turbulence over boulders and bedrock) until the canal is 100-200 feet above river level, whence the water drops abruptly through reinforced pipes (penstocks) driving turbines in the power plant.

Much of a river's excess energy is used to move sediment. The sediment load of a river can be broken into three components: dissolved load, suspended load, and bedload. Dissolved load consists of the products of rock weathering, such as Calcium, Magnesium, and Carbonate (CO_3), carried in solution. Where chemical weathering is the dominant denudation process on the landscape, such as in humid tropical regions or landscapes underlain by soluble limestones, dissolved load can constitute most of the sediment load. Elsewhere, dissolved load is usually a minor component of total load. Suspended load, the largest component of the sediment load of most rivers, consists of mud, silt, and sand maintained in suspension by turbulence in the water column. In general, the concentration of suspended sediment decreases with height above the bed. Bedload consists of sand and gravel moved along the bed of the river by rolling, sliding, and bouncing (saltating) (Figure 2). Although gravel may move in suspension during large floods, gravel is primarily transported as bedload, so to understand processes relevant to instream gravel extraction, we are particularly interested in bedload transport.

Bedload usually constitutes a small fraction of a river's total sediment load. In low-gradient rivers, bedload might constitute 2 percent or less of total load, while in mountainous terrain, bedload may constitute 20 percent of total load (Collins and Dunne 1987).

Sediment transport is one way in which rivers dissipate excess energy. If the sediment load of a river is artificially reduced without reducing the magnitude of the flows, the flows will still possess the excess energy capable of moving sediment, and the river will tend to erode its bed and banks.

The size of sediment grains movable depends on the water velocity (a function of water depth and channel gradient) of the flow, as illustrated by Figure 3. Flow velocity determines not only the size, but also the amount of sediment that can be moved in a river. The rate of sediment transport typically increases geometrically with flow, that is, a doubling of flow typically produces more than a doubling in sediment transport. This is illustrated by graphs relating transport of sediment in tons per day to the flow rate in the Carmel River (Figure 4). Because the rate of sediment transport is so much greater in higher flows, most sediment transport occurs during floods.

The sediment transported by rivers consists of the soil and rock fragments eroded from the watershed. The amount of sediment transported from a basin (the basin's <u>sediment yield</u>) can be used to compute the rate at which the landscape is lowered by erosion (the <u>denudation rate</u>). These processes are generally slow, with denudation rates ranging from under one-half inch per thousand years in the Appalachian Mountains to 40 inches per thousand years in the Himalayas (Leopold et al. 1964, p. 28). In general, the highest, steepest mountains are being most rapidly uplifted and are also being most rapidly eroded. For example, the Cropp River basin in the Southern Alps of New Zealand is being uplifted at approximately 0.4 inches per year and is being lowered by erosion at approximately the same rate (Griffiths and McSaveney 1983). Viewed over a longer perspective, runoff erodes the land surface and the river network carries the erosional products from each basin. The watershed can be divided into the zone of sediment production (steep, rapidly eroding headwaters), the zone of transport (through which sediment is moved more-or-less in equilibrium) and the zone of deposition (Schumm 1977)(Figure 5). The watershed can also be viewed as a sediment "factory", and the river channel as a "conveyor belt", which transports the products downstream to the ultimate depositional sites below sea level (Figure 5). Along the length of the river system, the size of sediment changes, from coarse gravel-boulder in steep upper reaches to sands and silts in low gradient reaches.

Along this "conveyor belt", sediment in the river bed may appear stable in the short term and may be replaced by new transient sediment every year or two. Gravel bars in the Eel and Mad Rivers may look much the same from year to year, but the majority of gravel particles in them may be replaced annually or biannually, as sediment moved downstream from this site is replaced by sediment carried in from upstream. The dynamic nature of river channel features may not be apparent, but is of enormous importance in understanding the effects of human activities on river channel morphology.

Just as the sediments in the channel bed are mobile on a time scale of years, so the sediments that make up the river <u>floodplain</u> (the valley flat adjacent to the channel) are mobile on a time scale of decades or centuries. The floodplain acts as a storage reservoir for sediments transported in the channel, alternately storing sediments (by deposition) and releasing sediment to the channel (by bank erosion). Figure 6 depicts migrations of the channel of the Carmel River since the first surveys in 1857. The river channel migrated over a quarter of a mile in places, with most channel shifts occurring during two large floods in 1862 and 1911. The 1911 flood deposited a wide channel of sand and gravel. By 1940, the Carmel River had cut a narrow channel 12 ft deep, leaving the flood-widened bed as a terrace of alluvium flanking the new active channel. By 1960, the terrace had been subdivided for low density housing, despite the recent origin of the land.

The floodplain is a dynamic feature closely related to the channel. In fact, the channel and the floodplain are best viewed as a single unit hydrologically and geomorphically, just as the watershed is a single landscape unit. Unfortunately, the natural functions of the floodplain have frequently been ignored, with often disastrous effects.

Flood Frequency and Channel Form

Except in unusual cases below large springs (such as Fall River near Burney), flow in California rivers is exceedingly variable. This is due to the highly seasonal precipitation and variable intensity of the winter cyclonic storms. Within the year, flows range from seasonal lows (in late summer in the Coast Ranges, in winter in higher elevation Sierran snowmelt streams) to high flows (during winter storms along the coast, during spring snowmelt at higher elevations). Flows also vary from year-to-year, depending on the abundance and intensity of precipitation for the year. The typical pattern of high flows is of particular importance in shaping a stream channel, especially for rivers flowing through sediments, less so for rivers flowing through bedrock canyons. One way to statistically summarize the flood regime of a river to compute the arithmetic average of the annual peak floods, the mean annual flood or Q_{maf}. However, because year-to-year variation in flood magnitude is so great in regions with semi-arid or Mediterranean climates (such as California), this statistic is very sensitive to the sequence of years that chance to fall within the period analyzed. For example, an average over the period 1955-1986 (encompassing wet years 1955, 1965, 1982, 1983, and 1986) would be higher than an average over 1956-1991 (excluding 1955 but including the dry years of 1987-1991). Distortion of estimating frequent events can be avoided by calculation of return periods of floods based on assumed distributions, as discussed below.

The history of floods on a given river can be analyzed to develop probabilistic estimates of the likelihood of a certain sized flood occurring in a year. The flood that occurs as the annual peak flow, on an average of every two years is the "two-year flood" or "Q_2"; the flood that occurs every ten years is the "Q_{10}". The probability that these flood levels will be reached or exceeded in any given year is 50 percent and 10 percent, respectively. It is a common misconception that if a river experiences a 100-year flood one year, the probability of a comparable flood the following year will be less. In fact, the probability of another 100-year flood the next year remains the unchanged at 1 percent.

It is intuitive that rivers with larger flows possess larger channels to convey the larger quantities of water. But how much larger must the channels be? More to the point, is there a flow to which the channel adjusts its geometry? During summer low-flows most rivers do not fill their banks, but occupy a small low-flow channel, exposing gravel bars and other such features. At extreme floods, the river flows out of its banks and spreads across its floodplain. The flow that just begins to exceed the capacity of the banks is designated as <u>bankfull flow</u>; in many rivers, this occurs at about the $Q_{1.5}$ to Q_2, (Leopold et al. 1964). This implies that many channels are adjusted to these frequent floods rather than to larger, but less frequent floods. However, the relative importance of less frequent floods is greater in semiarid and arid environments (Wolman and Gerson 1978).

<u>Effects of Reservoirs</u>

Dams and diversions have profoundly altered the character and functioning of rivers in California. To understand the nature of these changes, it is helpful to view them in terms of the independent variables that control alluvial channel geometry: flow regime and sediment load. Changes in these variables will produce adjustments in alluvial channels. The nature of these channel adjustments will depend upon the characteristics of the original and altered flow regime and sediment load. However, some general trends can be expected, as outlined in Table 1 and discussed below.

Dams disrupt the longitudinal continuity of the river system, interrupting the action of the "conveyor belt" of sediment transport. Upstream of the dam, all bedload sediment and most suspended load is deposited in the quiet water of the reservoir, while downstream, water released from the dam possesses the energy to move sediment, but no sediment load. Clearwater released from the dam is known as "hungry water", because the excess energy is typically expended on erosion of the channel bed and banks for some years following dam construction. For example, on Stony Creek (a tributary to the Sacramento River), since the closure of Black Butte Dam in 1963, the channel downstream has undercut and migrated laterally, eroding enough bedload sediment to compensate for about 20 percent of the bedload now trapped by Black Butte Dam on an annual average basis(Kondolf and Swanson 1993).

The channel erosion below dams is frequently accompanied by a change in particle size on the bed, as gravels are transported downstream, leaving a coarse <u>lag</u> deposit of cobbles or boulders, known as an <u>armor layer</u>. Development of the cobble-bed is an adjustment by the river to changed conditions because the larger particles are less easily mobilized by the hungry water flows below the dam. However, this change in particle size can be detrimental to salmon populations, which require gravels for spawning. This problem has been observed on many rivers in the state, including the American River below Folsom and Nimbus Dams, the Sacramento River below Shasta and Keswick Dams, the Mokelumne River below Comanche Dam, and the Carmel River below Los Padres and San Clemente. In these (and other) cases, gravels suitable for spawning have been artificially placed in the channel in an attempt to recreate the lost spawning habitat.

Reservoirs typically reduce flood peaks, although this effect varies considerably depending upon reservoir size and operation; flood control reservoirs can contain larger floods than reservoirs operated solely for water supply. The larger the reservoir capacity relative to river flow, the greater the reduction in peak floods. Downstream of the reservoir, encroachment of riparian vegetation into parts of the active channel may occur in response to a reduction in annual flood scour and sediment deposition (Williams and Wolman 1984). The process of vegetation encroachment is discussed further below.

Channel narrowing has been greatest below reservoirs that are large enough to swallow the river's largest floods, such as on the Trinity River after construction of Trinity Dam in 1960. Prior to dam construction, the Q_2 was about 16,000 cfs, after dam construction only about 300 cfs. The Q_{maf} decreased from 18,500 cfs pre-dam (1911-1960) to 2,600 cfs post-dam (1964-1990)(Figure 7). As a result of this dramatic change in flood regime, the dimensions of the channel have decreased since construction of the dam by encroachment of vegetation and deposition of sediment (Pitlick 1992).

In some cases, fine sediment delivered to the river channel by tributaries accumulates in spawning gravels because there are no more natural floods to flush the river bed clean. Probably the best known example in California is the Trinity River, where accumulation of decomposed granitic sand in the river bed has led to destruction of invertebrate and salmonid spawning habitat (Fredericksen and Kamine 1980). Experimental, controlled releases are now being conducted to determine the flows required to "flush" the sand from the gravels in the Trinity River (Kondolf et al. 1993).

Effects of Aggregate Mining

Aggregate in California is derived principally from pits located in active floodplains, inactive river terrace deposits, or directly in the active channel. Other sources include hardrock quarries and mining deposits within reservoirs. Although no figures are available to specify the proportion of total production derived from various sources, it is clear that the great majority of aggregate is derived from active channels and adjacent alluvial deposits.

Aggregate derived from active river beds has the advantage of requiring little processing or transportation. Natural river processes eliminate weak materials by abrasion and attrition, so the resulting deposits are durable, rounded, well-sorted, and relatively free of interstitial fine sediment. Gravel-bedded rivers are often located near the markets for the product or along transportation routes, which reduces hauling costs. This is especially important to this industry, where the cost of the product may double with each 25 miles of transport (Randy Sater, Teichert Construction Company, Sacramento, personal communication 1991).

As noted above, the sediment in the bed of rivers is a dynamic feature, in transit through the system during floods. The flux of bedload depends on the supply of coarse sediment from the watershed and the transporting power of the river. Transport rates vary over space and time. If the sediment flux is altered, the river channel is likely to adjust to the changed conditions. Instream gravel mining, by disrupting this sediment continuum, may alter a preexisting balance between sediment supply and transporting power.

The most dramatic effects of instream mining occur when pit mining is conducted within the active channel, inducing incision both downstream and upstream. As illustrated in Figure 8, the undisturbed channel is characterized by a continuity of energy available to transport sediment (designated here by shear stress, τ, the force per unit area exerted on the channel bed) and or sediment load. Because the pit traps gravel transported from upstream, it deprives downstream reaches of sediment supply. Downstream reaches still experience the same flow and therefore the same shear stress to move sediment, so the usual result is downcutting by the hungry water. By excavating large pits, whether shallow or deep, the profile of the stream bed is altered and the channel must adjust to the locally steeper gradient upon entering the pit (Figure 8). This steeper gradient creates an excess stream power capable of eroding the bed upstream. This process is known as "headcutting" or "knickpoint migration", and the effects may translate upstream for miles. As the streambed degrades, the material remaining on the surface will coarsen as sand and finer gravels are first transported, leaving a coarse lag similar to the armor layer seen downstream of dams. In severe cases, the degradation will continue until bedrock or older substrates under the recent alluvium are uncovered.

Incision has many direct effects, notably the undermining of bridge piers and other structures (Bull and Scott 1974). The Highway 299 Bridge over the Mad River has been undermined by channel incision resulting, at least in large part, from the cumulative effects of extractions upstream and downstream. The cost of extraction-related scour to bridges through 1984 in California probably exceeded $12 million (Kondolf and Matthews, in press).

When analyzing the impacts of various factors in the watershed, it is important to look some distance upstream and downstream for causes and effects. Actions changing runoff or sediment yield in distant parts of the drainage basin may affect river processes at a downstream site. For example, Benbow Dam impounds runoff and traps all bedload from 440 square miles of the South Fork Eel River watershed, reducing runoff and sediment delivery from about 12 percent of the drainage basin of the Eel River at Fernbridge. In many other California rivers, reservoirs affect a larger percentage of the drainage area. Incision under a bridge can be caused by instream gravel mines several miles upstream, which trap bedload and reduce sediment delivery to downstream reaches.

Incision can induce channel instability and trigger bank erosion and channel migration in formerly stable reaches. The physical alteration of the stream channel may result in destruction of existing riparian vegetation and reduction of available area for seedling establishment. Loss of vegetation affects riparian and aquatic habitat by loss of temperature moderating effects of shade and cover and loss of habitat diversity. As noted above, bed coarsening results in loss of spawning gravels for salmonids. Extensive degradation may induce a decline in the alluvial water table, as the channel acts as a drainage ditch, effectively draining the banks, affecting riparian vegetation and water supply wells (Woodward-Clyde Consultants 1976).

By altering the natural channel configuration, even low-volume gravel bar skimming operations can reduce habitat diversity by producing a wide, shallow channel lacking in the pools and cover needed by fish, and potentially increased water temperatures.

Vegetation Encroachment

Along many rivers in California, the active channel is maintained by scour in annual or biannual floods. In the seasonal decline of flow following the last flood of the season (during spring in rainfall-runoff streams of the Coast Ranges, during summer in the snowmelt-runoff streams of the Sierra and Cascades), seedlings of willows and other riparian trees begin growing on exposed areas of the active bed. However, these seedlings are normally scoured by floods that occur each year or two. The seedlings offer little resistance to the forces of flood scour and are easily swept away when the bed is mobilized. Thus, the open, unvegetated active channel is maintained.

However, if flood scour does not occur for several years, the seedlings can grow to maturity. Mature willows and other woody riparian species develop dense root mats that bind the sand and gravel of channel bed. As a result, the Q_2 is incapable of dislodging the mature plants. A much larger flow, on the order of the Q_{10} may be required to dislodge mature vegetation. Flood scour may not occur because of prolonged drought (as recently experienced from 1987-1992) or because of flow regulation by upstream reservoirs. Moreover, increased summer base flow below reservoirs may induce vegetation encroachment by irrigating the low-flow channel.

In order for vegetation encroachment to occur, the bed must be exposed (not submerged) during the germination period in late spring or summer because riparian vegetation cannot germinate under water. This factor is important because it prevents establishment of vegetation in rivers whose active channels are perennially submerged, as is commonly the case in more humid environments.

Soil moisture must be adequate during germination and growth of riparian seedlings. The water table may decline over the growing season, but the decline must be sufficiently gradual to permit root growth to keep pace. Soil moisture is determined by soil texture and water table depth. Coarse alluvial deposits (gravels and sand) retain little moisture above the water table (due to minimal capillary action); in these substrates water tables must be near the surface during the growing season for successful germination and survival. Finer-grained alluvial deposits (sand and silt) retain more moisture and permit plant growth with lower water table levels.

In wide, sand-bed channels with a shallow water table, vegetation can establish across virtually the entire active channel. Gravel-bed rivers typically have alternating bars with enough topographic relief that vegetation establishes primarily on sloping sides of the bars. One little-recognized effect of gravel bar skimming may be the potential for increased establishment of willow seedlings on skimmed surfaces. If skimming is not substantially rearranged or aggraded during the subsequent flow season, and provided riparian seedlings are not destroyed by operation of equipment, a shallower water table and therefore more favorable environment for seedling establishment may result (Figure 9).

In many channels dominated by boulders or cobbles, vegetation establishment is limited to the margins of the low-flow channel, as illustrated by the Merced River near El Portal (Figure 10). The zone in which plants can establish I have termed the "window of opportunity" (Kondolf 1988a), because above this zone, plants are desiccated in late summer, while below this zone, seedlings are periodically scoured by floods. Seedlings established above this window of opportunity are desiccated because the coarse-grained sediment cannot maintain adequate soil moisture as the water table undergoes its seasonal decline. Along the Merced River, we measured the maximum elevations of willow establishment above the baseflow level (of 1986), and found plants rarely established more than 1 m above the baseflow water elevation (which can be taken as a surrogate for the water table elevation in this coarse-grained alluvium). This finding is similar to patterns observed along Dry Creek, a gravel- and sand-bedded stream in Sonoma County, California. McBride and Strahan (1984) contrasted first year mortality in cottonwood and willow seedlings on a site with a shallow (20-cm deep) water table in September vs a site whose water table dropped to 1 m by September. All willow and 65 percent of the cottonwood seedlings died at the site with the 1-m deep water table, while the site with the 20-cm deep water table had survival rates of 12-38 percent for willow seedlings, 94 percent for cottonwood (McBride and Strahan 1984).

Encroachment of vegetation into active channels can have impacts on flood capacity of the channel. The San Joaquin River below Friant Dam has experienced a tremendous reduction in flood regime, and riparian vegetation has invaded the active channel as a result. The USACE has initiated a study of flood hazard resulting from loss of channel capacity due to vegetation encroachment (USACE 1991). Ironically, Friant Dam was constructed in part to provide flood control, but by controlling the frequent small floods, it has allowed vegetation establishment and created a flooding problem at lower flows. Kondolf and Matthews (1990) analyzed the potential reduction in channel capacity likely to result from enlargement of a reservoir (and reduction in the Q_2) on the Carmel River.

SEDIMENT BUDGET ANALYSIS

A sediment budget is an accounting of sediment sources, rates of sediment flux through the system, losses to or gains from temporary sediment storage reservoirs (such as gravel bars or floodplains), and losses by export from the basin. The basic sediment budget equation is

I +/- _S = O

where I = inputs, _S = change in storage, and O = output. For a given system, various components may be classified under input, storage, and output, depending upon how the system is defined.

For example, Kelsey (1980) developed a sediment budget for the Van Duzen River basin for the period 1941-1975, in which he defined five principal components of sediment input to the channel: fluvial sediment from hillslopes, debris slides and avalanches, earthflows, bank erosion in melange terrain, and bank erosion of floodplain and terrace deposits. He also measured change in storage, which was principally aggradation of the bed (mostly during the December 1964 flood), and he computed output from the river basin from suspended sediment concentration and flow data (Table 2). Kelsey's purpose was to develop a model for denudation of the Van Duzen River basin, showing the relative importance of various geomorphic processes and the relative importance of a large event, the 1964 flood.

By contrast, a sediment budget was developed for the Carmel River as a tool for management of the river downstream of San

Clemente Reservoir. For this budget there was no need to distinguish the geomorphic processes ultimately responsible for generation of sediment from the uplands. Rather, the budget established the importance of different sediment sources to the reach downstream of the dam: mainstem bank erosion, sediment yield from tributaries, and suspended sediment passing over the dam (Kondolf and Matthews 1991). In this study, based on extensive sediment sampling in 1982 and 1983, suspended and bedload sediment components were distinguished, permitting better resolution of the budget terms. The analysis showed that for the years studied, bank erosion was by far the dominant input term.

Sediment budget analysis can be helpful in analyzing potential impacts of instream gravel mining, especially in determining whether extraction rates approach or exceed annual bedload transport rates through the extraction reach. For example, Kondolf and Swanson (1993) developed a sediment budget for Stony Creek from Black Butte Dam to its confluence with the Sacramento River near Hamilton City (Figure 11). Stony Creek is a particularly good case to study because of the high natural bedload sediment yield, the magnitude of impacts of dam construction and instream mining, and the fact that the study reach (downstream of Black Butte Dam) traverses an alluvial fan so that there are no tributaries to complicate the picture. Prior to closure of Black Butte Dam in 1963, an annual average of about 100,000 m^3 (128,000 yd^3))of gravel was transported from the drainage basin to the study reach. Since closure of the dam, the reach below the dam has incised and laterally migrated, cannibalizing its earlier deposits, and regaining through bank erosion about 20 percent of its pre-dam sediment load. Using extraction volumes reported by the operators, an estimated 260,000-730,000 m^3 (330,000-930,000 yd^3) is removed annually along the entire length of Stony Creek, of which about 80-90 percent is concentrated in a 3-mile reach centered on the Highway 32 bridge. As a result of the intense mining upstream and downstream of the Highway 32 bridge, the channel degraded up to 17 ft between 1974 and 1990 under the bridge.

LIMITATIONS OF THE SCIENCE OF SEDIMENT TRANSPORT

Complexity of Natural Processes

The processes of bedload sediment transport in streams are still poorly understood. This is due, in large part, because it is generally not possible to observe the processes of bedload sediment transport directly, at least during times of greatest sediment transport. There is still basic disagreement among investigators about what goes on in streams during sediment transport. Moreover, it is difficult to measure bedload transport, especially during floods when the vast majority of sediment transport occurs. One reason sediment transport is so difficult to understand is the tremendous spatial and temporal variability in the processes of sediment production from the watershed, sediment delivery to the channel, transportation within the channel, and deposition in and along the channel. Transport rate is a function of both the transporting energy available and the volume and grain size of available sediment. In gravel-bed rivers, the nature of bedload transport changes with increasing flow when the force per unit area applied to the bed (the bed shear stress) becomes sufficient to disrupt the coarse surface layer (the pavement), liberating finer-grained particles from below. As a result, the rate of bedload transport at a given flow may be greater on the recession limb of a flood hydrograph than the rising limb. On the rising limb, the pavement was not yet disrupted and still "protecting" the underlying fine-grained sediment, while the pavement had not yet re-formed when the river dropped back to the same flow on the recession limb.

In addition, the supply of sediment available for transport may change over the course of a flood (as fresh landslides or bank erosion contribute new material to the channel) or over a period of years. For example, on the Carmel River, massive bank erosion in 1980, 1982, and 1983 delivered large quantities of sediment to the channel. Since then, a number of bank stabilization projects have been undertaken, and sediment input from this source (the largest source term in the sediment budget) has been reduced. Sediment transport measurements in 1992 and 1993 show the rate of sediment transport at a given flow has decreased from values measured in 1982 and 1983.

Even when the sediment supply and flow can be considered to be steady, large variations in bedload transport over time have been observed (Pitlick 1988, Carey 1985). In field studies on the Trinity River in 1992 (Kondolf et al. 1993), the author collected ten sequential replicate Helley-Smith samples of bedload transport at the same station during a reservoir release held steady for a period of six days. The measured transport rates varied by over 100 percent. On sand-bedded streams, dramatic variations in transport rate are known to be associated with the passage of dunes and related bedforms. Similarly, large-scale bedforms known as "gravel waves" (about 1 m high and 1 km long) have been observed on the Waimakariri River near Christchurch, New Zealand, moving downstream at about 1 kmy^{-1} (Griffiths 1979).

On the Trinity River (and elsewhere) bedload transport rates were observed to vary substantially across the channel, with transport concentrated in zones. If these zones migrate across the channel (much as the boundaries between eddies and the main current can be observed to migrate), this would also cause bedload transport rate to vary at a point.

For these and other reasons, the relationship between sediment transport and flow is usually scattered. The sediment rating curve is usually developed as a best-fit line through often widely scattered data to predict the dependent variable (sediment transport) from the independent variable (flow)(Figure 4). The most common practice to compute total annual sediment transport is to apply a sediment rating curve to the annual hydrograph. The inherent imprecision of the "rating curve" approach to computation of total suspended sediment transport has been discussed by Walling (1977), and Glysson (1987) documented errors of from 0 to 1,760 percent from this approach.

Limitations of Sediment Transport Models

Sediment transport models can be useful tools in analysis of river systems, but it is unrealistic to treat model predictions as anything more than attempts to represent, in a very simplified fashion, an exceedingly complex natural system that is still poorly understood. For their input values, sediment transport models must simplify river channel geometry and bed material size. For actual computation of sediment transport, the models must simulate flows in the river and use one of many conflicting sediment transport equations. Given this, the state-of-the-art in modeling sediment transport is simply not good enough to accept results of a model when those results contradict general principles of river behavior and observations on streams in the region.

Existing equations to predict sediment transport were developed (or calibrated) using imperfect field data (and data from laboratory flumes that may not reflect field conditions). The equations are unlikely to be better than the measurements upon which they were based. Given this, it is not surprising that a recent study by the National Research Council (NRC) concluded that use of these models "...cannot be justified in flood insurance studies." (NRC 1983, p.xi) The American Society of Civil Engineers compared numerous sediment transport equations with each other and with field data and concluded "...it is clear that sediment discharge formulas, at best, can be expected to give only estimates." (Vanoni 1977, p. 229-230)

Comparison of Models

A recent study by the National Research Council (NRC 1983) tested six computer models of sediment transport, including HEC-6 and FLUVIAL-11, and reported that "...greatly different sediment discharges were predicted by the models tested in this study" (p.114), and concluded that the use of these models "...cannot be justified in flood insurance studies." (p.xi) The report identified the principal deficiencies of sediment transport models as follows:

> "a. Unreliable formulation of the sediment-discharge capacity of flows.
>
> b. Inadequate formulation of the variable friction factor of erodible-bed flows, and, in particular, the dependency of friction factor on depth and velocity of flow, sediment concentration, and temperature.

> c. Inadequate understanding and formulation of the mechanics of bed coarsening and armoring, and their effects on sediment-discharge capacity, friction factor, and degradation suppression of flows.
> d. Inadequate understanding and formulation of the mechanics of bank erosion, and therefore, limited capability to incorporate this contribution into the sediment input to the flows from bank erosion and the effects of channel widening." (NRC 1983 p.xi-xii)

It is worth emphasizing that any sediment transport model is only a simplification and generalization of what are actually complex field conditions. This process of simplification and generalization involves a great many assumptions. As was illustrated by NRC study, several different competent people running the same models can produce several different results.

Problems with Sediment Transport Equations

As noted by the NRC (1983), one of the biggest problems with sediment transport models is that existing sediment transport equations (on which the models are based) are unreliable predictors of sediment transport. The American Society of Civil Engineers (ASCE) manual on Sedimentation Engineering compared the predictions of various sediment transport equations on the same data set and showed that the predictions differed up to a factor of 100. The ASCE concluded,

> Based on the material presented it is clear that sediment discharge formulas, at best, can be expected to give only estimates...
> It is very desirable to give guide lines that will enable the engineer to select an appropriate formula or relation that is suitable for use under any specific set of conditions. Unfortunately, this cannot be done except in a very general sort of way. A rough way to judge the suitability of a formula is to compare the characteristics of the flows in the problem at hand with those of the flows that gave the data for determining the formula...It must be emphasized that the foregoing method of judging the suitability of a formula is a rough one and may not give satisfactory results. For this reason it is recommended that the selection of a formula or formulas be based on checking calculated sediment discharge against any observed values of the stream under consideration or on similar ones. Finally, after reasonable checks have been made one can then make some kind of judgement of the reliability of the calculations that should be kept in mind in using them in the planning works. (Vanoni 1977, p.229-230.)

Uncertainty in Geomorphic and Sediment Transport Predictions

Some degree of uncertainty is inevitable in the study of channel change and sediment transport. This is so because: 1) numerous independent watershed variables (e.g., rainfall, rock type, land use) can combine in many different ways to produce different flow and sediment regimes, and 2) numerous dependent channel variables (e.g., width, depth, bedforms, sediment transport) can adjust in many different combinations to any given regime (the indeterminate hydraulics described by Maddock 1970). Put another way, there are too many variables to solve all the equations simultaneously.

Given the impossibility of exact prediction from science and engineering, geomorphic understanding assumes increasing importance. Although computer models are limited, there is often much historical evidence available to provide insights into the response of a river to particular types of events.

THE NEED FOR HISTORICAL STUDIES

Every river is unique. Given the complexity of natural sediment transport, the indeterminate nature of channel hydraulics, the inability of simplified models to adequately predict river behavior, and the variety of human influences upon river systems, the best guide to a river's future behavior is often gleaned from analysis of its past behavior. Moreover, a historical perspective is essential to placing the present condition in context. In California, large infrequent floods may reshape the channel, stripping the riparian zone of vegetation, transporting boulders, and eroding or depositing large quantities of sediment. The catastrophic channel changes occur suddenly, but recovery may take decades. We might develop a very different picture of the same stream depending upon whether we observe it two or twenty years following a big flood. We must know the channel's history of flood response and recovery to know what we are looking at in any given year and what changes we might expect.

For example, the Marble-Cone Fire burned large portions of the drainage basin of the Arroyo Seco (a tributary to the Salinas River south of Carmel Valley) in 1977. In 1978 and 1980, increased erosion from the burned area resulted in about six feet of aggradation in parts of the channel, but a decade later, the bed had returned to its pre-fire profile. First, it would be important to know that the basin had just burned if we were studying the Arroyo Seco in 1981. Moreover, documenting the past channel response to a perturbation such as this provides an indication of the system's resilience to future, similar events: the Arroyo Seco accommodated dramatically increased sediment loads without inducing widespread instability.

Sources of data for historical channel stability analysis include historical aerial photographs (coverage extends back to the 1930's for most of California), old maps (commonly back to the 1850's), old engineering surveys of some river reaches (possibly back to about 1900), surveys under bridges at construction, computed bed elevations from gaging station records, narrative accounts, and geomorphic evidence (Kondolf and Sale 1985).

Geomorphic evidence would include such features as a deeply buried redwood stump encountered in an excavation along the Eel River, as reported by a participant during the author's presentation in Eureka in December 1992. If this stump were to be dated by C_{14} analysis, it might provide an excellent data point for reconstruction of the river's history. In the historical analysis, this evidence would be compared to other evidence, such as the report in 1917 that the Eel River was tidal (with a low tide depth of 2 ft) for six miles upstream from the mouth (64th US Congress 1917). However, accumulation of gravel over the stump could result from down-dropping of the land (resulting from tectonic movements) as well as an increased delivery of sediment from the watershed.

An example of temporarily increased sediment yield from a basin is the passage of hydraulic mining debris through the Yuba River around the turn of the century. Hydraulic mining was conducted by directing high-pressure jets of water onto an exposed placer deposit (gravel, sand, and silt) and running the sediment through sluices to remove the gold (Yeend 1974), washing away large portions of mountains, leaving canyon-like landscapes (e.g., Malakoff and Columbia Diggins state historic parks). The sediment washed into steep canyons and thence into the Central Valley, increasing the load of the Yuba and Feather Rivers beyond their transport capacity, resulting in extensive deposits of sediment at the foot of the Sierra Nevada. The "debris plain" of the Yuba River was particularly noteworthy, covering over 40 square miles east of Marysville. As river channels filled with sediment, rivers flooded farmland, inundating many fields with fresh deposits of hydraulic mining debris. Agricultural interests successfully halted the practice of hydraulic mining (which had begun in the 1850's) in the courts in 1884.

The passage of this wave or "slug" of sediment through the Yuba River was documented by changes in bed elevation at the stream gage at Marysville, which showed aggradation had peaked and the bed began incising by 1905 (Figure 12)(Gilbert 1917, Adler 1980). Stabilization of the bed of the Yuba River continued for decades, influenced in large part by channel training works and construction of Englebright Dam in 1940 upstream of the debris plain. The Highway 20 bridge over the Yuba River at Parks Bar was constructed in 1911, when the bed was still aggraded from the influx of the mining debris. As the channel recovered over the subsequent decades, flushing out the aggraded sediment, the bridge piers were undermined (Kondolf 1988b). An instream gravel mine immediately upstream of the bridge may have contributed to the incision at the bridge, but the largest factor was probably gradual recovery from the hydraulic mining debris.

On Redwood Creek, repeated channel surveys documented aggradation and incision resulting from passage of a wave or "slug" of sediment, which migrated downstream about 15 miles over a decade (Varnum and Ozaki 1986).

INSTREAM MANAGEMENT STRATEGIES

A number of approaches have been employed to monitor instream extraction, based either on limits to extraction quantities or observed channel effects. One approach is to estimate the "replenishment rate" (the rate at which gravel is transported into the extraction reach from upstream), and to permit that quantity to be mined. The replenishment rate is usually expressed as an annual average, although in some cases it is estimated on a year to year basis. Because of the episodic nature of sediment transport and the enormous year-to-year variability in transport, an annual average replenishment rate is of questionable value: it will rarely correspond to the actual transport in a given year. Moreover, because of the uncertainties in sediment transport estimation and prediction, estimates of transport are prone to honest error or can be deliberately manipulated. More fundamentally, however, this approach ignores the continuity of sediment transport through the system.

The notion is that if the harvest rate does not exceed the rate at which coarse sediment is delivered from upstream, the harvesting can be sustained without impact on the channel system. However, when viewed in the larger context, this extraction site can be seen as the "upstream" from which downstream reaches derive their coarse sediment supply. If the sediment in transit through the system is rerouted out of the channel into gravel trucks, the flow of gravel is interrupted and downstream reaches are deprived of their sediment load. One effect of this is creation of hungry water downstream of extraction sites, and the river may expend its excess stream power by eroding bed and banks. Thus, channel incision and instability may result downstream of extraction sites even if the extraction rate does not exceed the "replenishment rate".

Another approach is to limit the depth of extraction, but unless this is expressed in terms of an absolute elevation, the constraint may be meaningless. Permits often specify "x feet below the channel bed" or prohibit excavation "below the water level" without defining the water level. Similarly, an approach used in Mendocino County and elsewhere has been to prohibit excavation below the thalweg, but the thalweg is redefined each year. Such approaches deal only with the excavation itself, not with resulting degradation, which can result in progressively lower bed elevations. In general, CDFG and county permits tend to focus on the short-term impacts of extraction (gasoline spill, turbidity during operation), ignoring cumulative effects of all extractions over time, such as degradation of the river bed.

A more meaningful approach is to define limits to degradation expressed in reference to permanent benchmarks, commonly termed a "redline", as used by Ventura County on the Santa Clara River. River bed elevations can be documented by repeated aerial photography (as used by Sonoma County) or by resurvey of channel cross sections by registered engineers (as done by Lake County). These approaches provide important information for making resource decisions, but the need for a historical study cannot be overstated. For example, a river may be undergoing a long term adjustment to a major aggradational flood and would be downcutting its bed in any event. If this context were not understood, degradation observed in measured cross sections might be erroneously attributed solely to effects of extractions.

COMPREHENSIVE ENVIRONMENTAL PLANNING

The present practices and regulation of instream mining have evolved piecemeal over recent decades in reaction to problems resulting from increased extraction rates related to the state's rapid urban growth. Despite the fundamental economic importance of the aggregate, and despite the environmental impacts of its extraction from river channels, the existing situation has developed without the benefit of objective, regional planning, in which society can make businesslike decisions about the alternatives for extraction and allocation of these resources.

There has been little serious effort to step back and view these issues in the larger context of environmental impact within the entire river basin and the range of aggregate sources available in a region. Decisions about managing these resources should be based on adequate information about both the resource quality and uses, and the environmental impacts of various alternatives. Unfortunately, in many areas, the necessary data are lacking or have not been compiled in a meaningful way.

County or regional-level planning is needed to:

1) Analyze market demand for aggregate (recent history, present demand, and future projections). The demand analysis should be sufficiently sophisticated to specify the quality of product needed for each end use.

2) Inventory potential sources of aggregate regarding both quantity and quality. These sources should include all older gravel deposits, especially those outside the riparian zone, potential quarry rock sites, and recycled aggregate. In addition, production costs and transportation costs to various markets should be estimated.

3) Evaluate and quantify environmental impacts of extracting from each source. Some impacts (such as the noise level in a residential neighborhood from a quarry) may be relatively easy

to quantify. Other impacts (such as the effects of extractions on channel behavior and bridge integrity) may be more difficult. In any event, the cumulative impacts of each alternative should be evaluated to the extent possible.

Until recently (and still in many areas) environmental costs of instream gravel extraction have not been factored into production costs, making instream sources more attractive than alternatives such as dry terrace mines (which often require additional processing), quarries (from which rock must be crushed, washed, and sorted), or distant sources, such as reservoir deltas, involving greater transportation costs. Also, in many areas, competition for land from urbanization or agriculture has pushed aggregate mines into stream channels.

However, with the loss of most of California's riparian forests over the past 150 years and increasing recognition of the ecological importance of these habitats (terrestrial and aquatic), resource agencies are becoming reluctant to permit further operations without adequate environmental review.

Identification of Alternative Aggregate Sources

To identify potentially valuable mineral reserves in a region and to prevent them from being paved over and rendered inaccessible by urbanization is one goal of SMARA. Toward that end, the State Mines and Geology Board (the Board) has completed surveys of potential aggregate minerals in "production-consumption regions" in 18 counties. These have been published as "Mineral Land Classification" reports (e.g., CDMG 1982). The Board has also then designated certain reserves as "Regionally significant construction aggregate resources areas" within the production-consumption region (e.g., CDMG 1984). This designation puts certain restrictions on development of the land. For the past two years, the Board has stopped designating "regionally significant" resources to avoid the requirement to produce environmental impact documents. The Board has also shifted to producing county-level mineral assessments that include minerals other than aggregate minerals.

The Board's limited budget and staff have resulted in slow progress in classifying mineral lands in the state. Twenty counties (including Humboldt, Mendocino, Del Norte, Trinity, Siskiyou, and Shasta) have yet to have any such classification done. Figure 13 shows areas in California that have classification reports completed or in progress as of June 30, 1991. Although Humboldt County has been on a list for eventual classification study, the Board assigns highest priority to rapidly urbanizing counties in central and southern California (Mike Sandecki, CDMG, personal communication 1993).

It is possible that County officials could petition the Board to conduct a mineral land classification study of Humboldt County sooner than presently scheduled. However, normal delays would likely mean several years before such a study was complete and available as a basis for decision making in Humboldt County. Accordingly, identification of potential upland and terrace aggregate sources will probably need to be done by the County.

The EIR for Gravel extraction from the Lower Eel River (Humboldt County 1992) dismissed alternative aggregate sources as infeasible without an adequate exposition of the supporting analysis. The County Materials Testing Lab inventoried existing pits in remote areas of the county, and found most to yield weak lithologies unsuitable for most aggregate applications, although 25 percent of the existing pits yield rock suitable as aggregate base. This was consistent with county engineers' long-term experience with behavior of materials on county roads, indicating most of the rock west of the South Fork Eel to be "soft" (Don Tuttle, Humboldt County Public Works). However, it is not clear that the population of existing pits is a representative sample of the distribution of geologic units in the county from which potential aggregate sources could be identified. In any event, it should make no difference if most of the county is underlain by incompetent lithologies so long as a few suitable quarry sites can be located and developed. Thus, while valuable experience gained by county engineers should not be discounted, a fresh look at potential sources of aggregate is needed in a comprehensive and systematic fashion.

The EIR also argued that about $1 million worth of crushing equipment would be required at a quarry and dismissed the option because, "The cost to the consumer for aggregate base or whatever gravel material would double" (Humboldt County 1992:164). The assumptions and calculations used to reach this conclusion were not presented in the EIR, but this sort of economic argument demands careful analysis and recognition that while instream aggregate sources may require less processing, they are not necessarily "free" when environmental impacts are considered. While the information collected on upland quarries thus far is useful, potential upland sources for aggregate (bedrock and terrace gravels) should be systematically inventoried as an essential element of the County's aggregate management plan.

Aggregate recycling has been identified as a potentially significant source in Sonoma County (Sonoma County 1992) and is now commercially available in some areas. In recent negotiations over highway construction, the City of Albany required Caltrans to use only recycled aggregate (Mike Brodsky, personal communication 1993). Concrete rubble suitable for recycled aggregate is likely to be more available in urban areas than in Humboldt County, but to the extent that it is available, incentives should be created to encourage its use as a resource rather than its disposal as waste.

Matching Aggregate Quality with End Use

One important aspect of a mineral resource inventory or land classification is matching aggregate quality with end use.

Sources of PCC-grade aggregate should be identified. At present, these are mostly river-derived aggregate. This product should be used, to the extent possible, only in applications requiring the PCC-grade quality. It is likely that upland quarry or terrace pit sites can be identified to produce lower grade aggregate for road bed and other uses. Increasing the efficiency of resource allocation makes sense in that it preserves the most valuable resources for the highest end uses.

In addition to compilation of economic and environmental data as a basis for decision-making, there are equity issues to be addressed. Given the competitive nature of the aggregate business, some mechanisms must be developed to insure that any increased restrictions on instream mining are phased in to avoid unfair competitive advantage to certain operators. In the long run, incorporation of true environmental costs into the price of river-produced aggregate will stimulate competition and render upland sources more attractive.

It is virtually inevitable that upland quarry sites will trigger local, probably vocal, opposition. While these concerns should be considered, they must be viewed in the larger perspective. There is a danger that institutional inertia and NIMBYism (the "Not-In-My-Backyard" opposition that develops to virtually any land-use proposal) could make it easier politically to maintain a status quo that may produce large environmental (and economic) impacts to important public resources than to make changes that would reduce overall impacts, but would shift those impacts to a small (probably vocal) segment of the public.

If the environmental effects of instream mining are too great, and if we can't locate upland quarries or pits, then we have no aggregate, and construction comes to a halt in the county. Clearly, there are choices to be made. These choices can be made wisely only in the context of all possible aggregate sources and an appreciation for the cumulative effects of their extraction. Making these choices poses a challenge not only to county government, but also to environmental and citizen advocacy groups, who cannot oppose all proposed aggregate extractions without inviting economic disaster. The regional context must be borne in mind when advocating specific, local land use decisions. It may prove necessary to accept traffic and noise impacts near an upland quarry to achieve the greater benefit of reducing instream extraction. In such cases the impacted residents can be compensated.

The management of aggregate resources in Humboldt County poses a challenge that cannot be successfully addressed piecemeal. Through comprehensive regional planning, in which economic and environmental consequences of various alternatives are recognized and quantified, an equitable, efficient, and environmentally-sound resolution can be found.

RECOMMENDATIONS FOR NEAR-TERM ACTIONS BY THE COUNTY

At present, the County is under pressure to prepare an EIR that can be approved by 1 June 1993 in order to permit extractions to resume in the Mad River this summer. Without the EIR, regulatory agencies may not issue permits for mining in the Mad River. However, the essential studies needed as a basis for comprehensively assessing environmental impacts and for reaching sensible resource allocation decisions have not yet been completed. Specifically:

1) A historical channel study is needed for the Mad River to put the present river conditions in long-term perspective. This study could possibly be completed this spring, but 9-12 months is a more reasonable time frame.

2) A sediment budget should be constructed from results of the historical study as well as reservoir sedimentation data, inventory of sediment stored in-channel and in terraces, and other quantification of sediment sources, transport, and storage. As with the historical study, 9-12 months is reasonable time frame for a sediment budget study.

3) A thorough inventory should be made of all potential aggregate sources in the region, including upland quarry and terrace sources. This study will require analysis of existing geologic maps as well as field checking and reconnaissance, testing of potential aggregate quality, and land ownership surveys. The study should not be limited to the Mad River drainage, but should include the entire market area. It is unlikely that such a study could be completed by June, although 9-12 months is probably enough time.

4) An economic analysis of alternative sources should be conducted, taking into account not only production and transportation costs, but also estimated environmental costs of indirect effects of instream extraction.

5) Based on results of the above studies, an aggregate management plan for the market area should be proposed. This plan should include a strategy for phasing in any alternative sources of aggregate, and matching aggregate quality with end use.

If it is true (as argued here) that an informed aggregate management strategy and substantiated EIR can be based only upon the results of these studies, then it would make sense to postpone the EIR until these studies can be completed. Postponing EIR preparation by one year will probably fail to satisfy the requirement of regulatory agencies that an EIR be completed this year. However, it is highly unlikely that a comprehensive aggregate resource management plan, in which environmental issues or upland alternatives are fully evaluated, can be completed by June. Thus, the dilemma.

A possible solution to the problem would be to commence the historical study and study of upland alternatives immediately, using funding available for the EIR preparation. (The historical and sediment budget analyses completed this spring by Andre

Lehre, Randy Klein, and colleagues appear to constitute an excellent beginning.) A preliminary EIR can be prepared this year, which would outline the strategy of conducting the studies, developing a rational aggregate management plan next year, and preparing the EIR based on the plan and study results. Given the environmental benefits from a plan that realistically analyzed cumulative effects and considered all alternatives, it is likely that the regulatory agencies would approve the preliminary EIR and throw their support behind the necessary studies and the comprehensive environmental planning effort to follow. These agencies should be involved in formulation of the aggregate management plan next year.

Studies of the Eel River should be coordinated with those on the Mad. The EIR on the Lower Eel River (Humboldt County 1992) represents an excellent first step at recognizing the environmental impacts and incorporating historical information in the analysis. However, a more thorough historical study is needed on the Lower Eel River, involving resurveys of historic cross sections and mapping of old channel courses from historical maps and photographs.

ACKNOWLEDGEMENTS

This study was prepared for, and partially supported by, the County of Humboldt, Planning Department. In preparing this report, I have benefitted from discussions with and/or review comments from Bill Davis, Tom Hofweber, Randy Klein, Melissa Martel-Accetta, Lisa Micheli, Sidnie Olson, Bill O'Neill, Mike Sandecki, Mitch Swanson, Don Tuttle, and Jennifer Vick.

REFERENCES CITED

Adler, L.L. 1980. Adjustment of the Yuba River, California, to the influx of hydraulic mining debris, 1849-1979. MS thesis, Univ. of California, Los Angeles. 180 pp.

Bull, W.B., and K.M. Scott. 1974. Impact of mining gravel from urban stream beds in the southwestern United States. Geology, April 1984:171-174.

Carey, W.P. 1985. Variability in measured bedload-transport rates. Water Resources Bulletin. 21:39-48.

CDMG (California Division of Mines and Geology). 1982. Mineral land classification: aggregate materials in the Western San Diego County Production-Consumption Region. CDMG Special Report 153.

CDMG (California Division of Mines and Geology). 1984. Designation of regionally significant construction aggregate resource areas in the Western San Diego County Production-Consumption Region. Prepared under the direction of the State Mining and Geology Board, Sacramento CA.

Collins, B., and T. Dunne. 1987. Assessing the effects of gravel harvesting on river morphology and sediment transport: a guide for planners. Report prepared for State of Washington Department of Ecology.

Frederiksen, Kamine, and Associates. 1980. Proposed Trinity River Basin Fish & Wildlife Management Program. Report to US Department of Interior, Water and Power Resources Service, Frederiksen, Kamine, and Associates, Sacramento CA.

Gilbert, G.K. 1917. Hydraulic mining debris in the Sierra Nevada. US Geological Survey Professional Paper 105.

Glysson, G.D. 1987. Sediment transport curves. US Geological Survey Open-File Report 87-218. 47 pp.

Griffiths, G.A. 1979. Recent sedimentation history of the Waimakariri River, New Zealand. Journal of Hydrology (New Zealand). 18:6-28.

Griffiths, G.A., and M.J. McSaveney. 1983. Hydrology of a basin with extreme rainfalls - Cropp River, New Zealand. New Zealand Journal of Science. 26:293-306.

Humboldt County (Natural Resources Division, Public Works Department). 1992. Final program EIR on gravel removal from the Lower Eel River. Eureka, CA. July 1992.

Kelsey, H.M. 1980. A sediment budget and an analysis of geomorphic process in the Van Duzen River basins, north coastal California, 1941-1975. Geological Society of America Bulletin, Part II v.91:1119-1216.

Kelsey, H.M., M.A. Madej, J. Pitlick, M. Coghlin, D. Best, R. Belding, and P. Stroud. 1981. Sediment sources and sediment transport in the Redwood Creek basin: a progress report. 114 pp. Redwood National park, Arcata CA.

Kondolf, G.M. 1982. Recent channel instability and historic channel changes of the Carmel River, Monterey County, California. MS thesis, University of California at Santa Cruz.

Kondolf, G.M. 1988a. Interactions between riparian vegetation and channel form. Remarks to the California Riparian Systems Conference, Davis CA, September 1988.

Kondolf, G.M. 1988b. Historical channel stability analysis and assessment of spawning gravels in the Lower Yuba River. Report submitted to Beak Consultants, Sacramento, CA by Philip Williams and Associates, San Francisco. April 1988.

Kondolf, G.M., and W.V.G. Matthews. 1990. Assessment of potential impacts of Monterey Peninsula Water Supply Project Alternatives on downstream channel geometry of the Carmel River. report to the Monterey Peninsula Water Management District.

Kondolf, G.M., and W.V.G. Matthews. 1993. Management of coarse sediment in regulated rivers. University of California Water Resources Center, Davis. (in press)

Kondolf, G.M., and M.J. Sale. 1985. Application of historical channel stability analysis (HCSA) to instream flow studies. in Proceedings of the Symposium on Small Hydropower and Fisheries. F.W. Olsen, R.G. White, and R.H. Hamre, eds., American Fisheries Society, Bio-Engineering Section and Western Division, May 1-3, 1985. Denver CO. p.184-194.

Kondolf, G.M., and M.L. Swanson. 1993. Channel adjustments to reservoir construction and gravel extraction along Stony Creek, California. Environmental Geology and Water Science. (in press).

Kondolf, G.M., W.V.G. Matthews, J.L Parrish, P.R. Wilcock, A.F. Barta, C.C. Shea, and J.C. Pitlick. 1993. Determination of flushing flow requirements in the Trinity River below Lewiston Dam: a progress report. in Proceedings of the conference on decomposed granitic soils, Redding CA, October

1992, University of California Extension, Davis. (in press)

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman and Co., San Francisco.

Maddock, T., Jr. 1970. Indeterminate hydraulics of alluvial channels. Journal of the Hydraulics Division, American Society of Civil Engineers. 96:2309-2323.

Matthews, W.V.G., and G.M. Kondolf. 1993. Assessment of channel forming discharge for the Carmel River. unpublished report to Monterey Peninsula Water management district, Monterey, California.

McBride, J.R., and J. Strahan. 1984. Fluvial processes and woodland succession along Dry Creek, Sonoma County, California. in California Riparian Systems, R.E. Warner and K.M. Hendrix, eds., University of California Press, Berkeley. p. 110-119.

NRC (National Research Council). 1983. An evaluation of flood-level prediction using alluvial-river models. Committee on Hydrodynamic Computer Models for Flood Insurance Studies, Advisory Board on the Built Environment, Commission on Engineering and Technical Systems, National Research Council. National Academy Press, Washington DC. 127 pp.

Pitlick, J. 1988. Variability of bedload transport. Water Resources Research. v.24:173-177.

Sandecki, M. 1989. Aggregate mining in river systems. California Geology. 42:88-93.

Schumm, S.A. 1977. The Fluvial System. Wiley & Sons. New York.

Stine, S. 1987. Mono Lake: the past 4,000 years. Ph.D. thesis, University of California, Berkeley, Geography Department.

USACE (US Army Corps of Engineers). 1991. Notice of initiation of reconnaissance study for flood control, San Joaquin River mainstem and tributaries, California. USACE Sacramento District, 3 pp.

US Congress, 64th Session. 1917. Document 2100, Letter from the Secretary of War.

Vanoni, V., ed. 1977. Sedimentation Engineering. American Society of Civil Engineers, Manuals and Reports on Engineering Practice No.54.

Varnum, N., and V. Ozaki. 1986. Recent channel adjustments in Redwood Creek, California. Redwood National Park Technical Report 18.

Walling, D.E. 1977. Limitations of the rating curve technique for estimating suspended sediment loads, with particular reference to British Rivers. International Association for Scientific Hydrology. Publication 122:34-48.

Williams, G.P., and M.G. Wolman. 1984. Downstream effects of dams on alluvial rivers. US Geological Survey Professional Paper 1286.

Wolman, M.G., and R. Gerson. 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes and landforms. 3:189-208.

Woodward-Clyde Consultants. 1976. Aggregate extraction in Yolo County - a study of impacts and management alternatives: Aggregate Resources Advisory Committee, County of Yolo Planning Department.

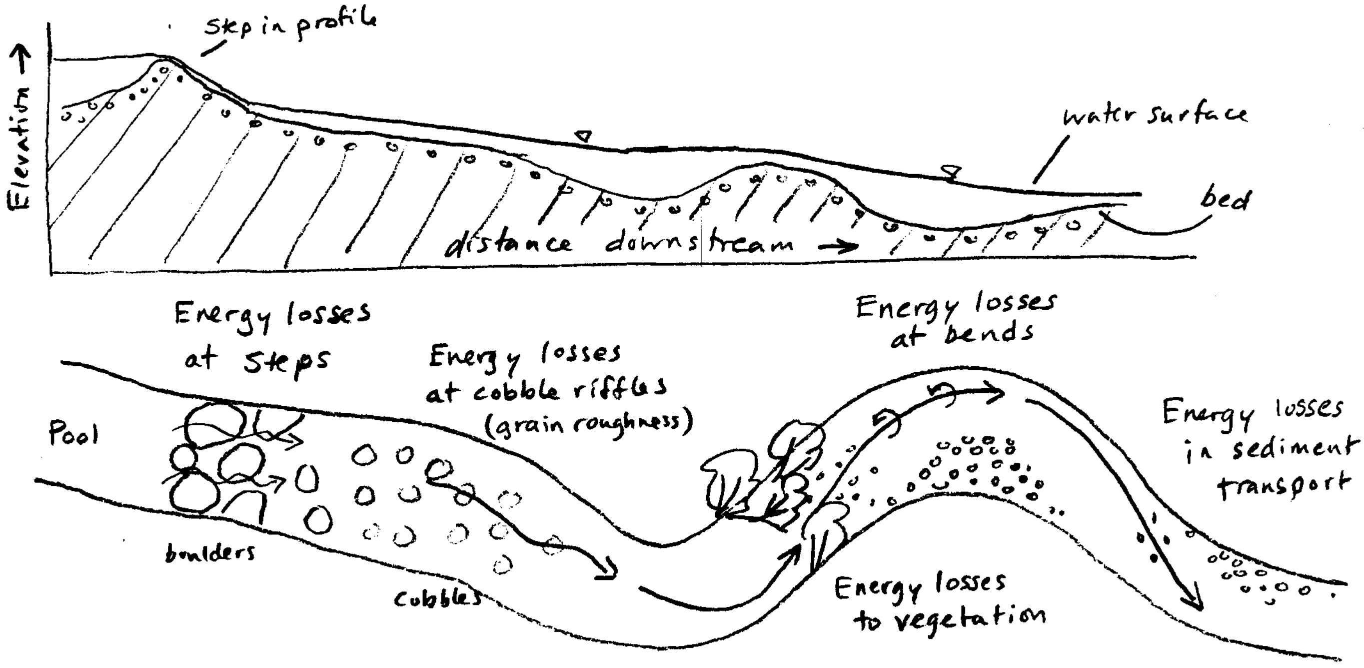


Figure 1. Diagram of energy dissipation in river channels.

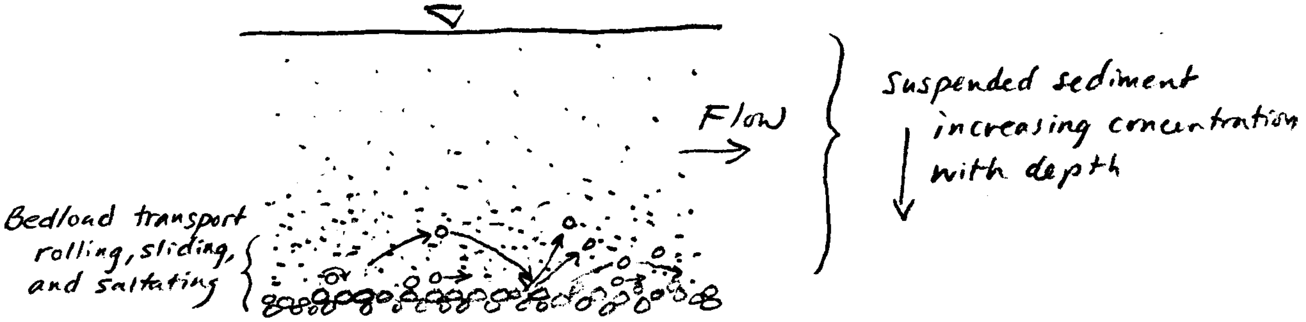


Figure 2. Suspended and bedload sediment transport in river channels.

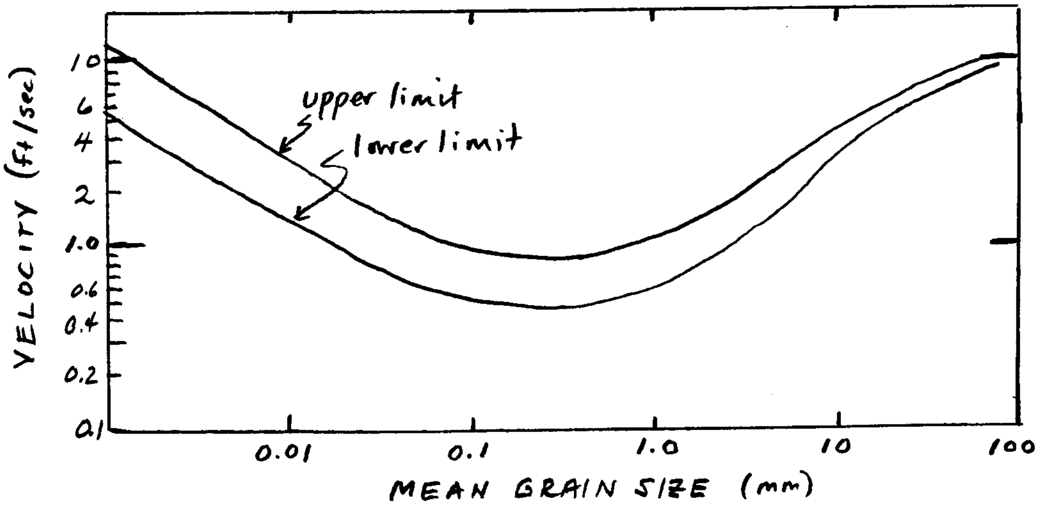


Figure 3. Relation between flow velocity and transport of uniform-sized quartz grains. (adapted from Vanoni 1977)

FIGURE 4

BEDLOAD TRANSPORT RATING CURVE
CARMEL RIVER near CARMEL

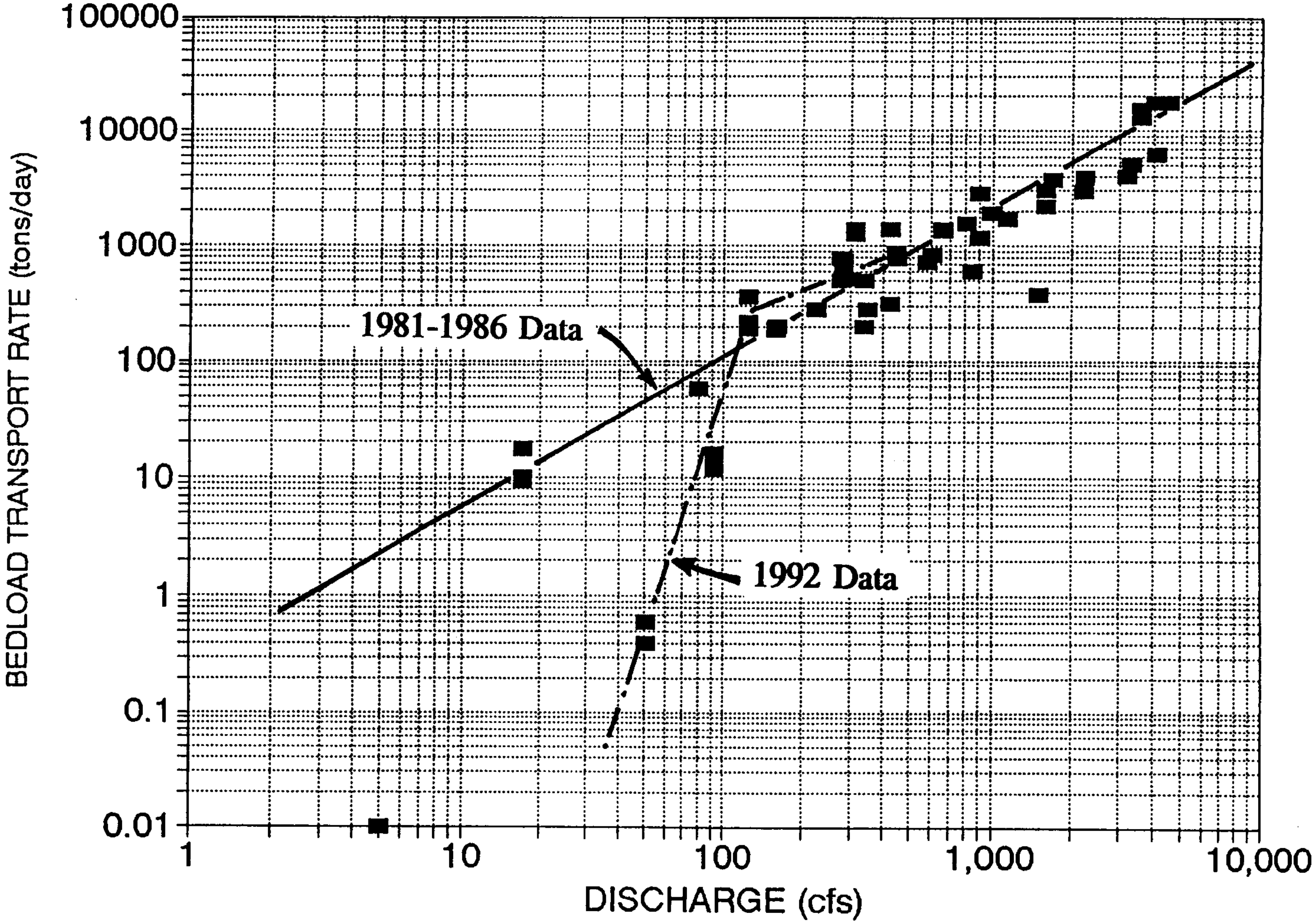


Figure 4. Relation between sampled bedload transport rate and flow in the Carmel River near Carmel. (Source: Matthews and Kondolf 1993)

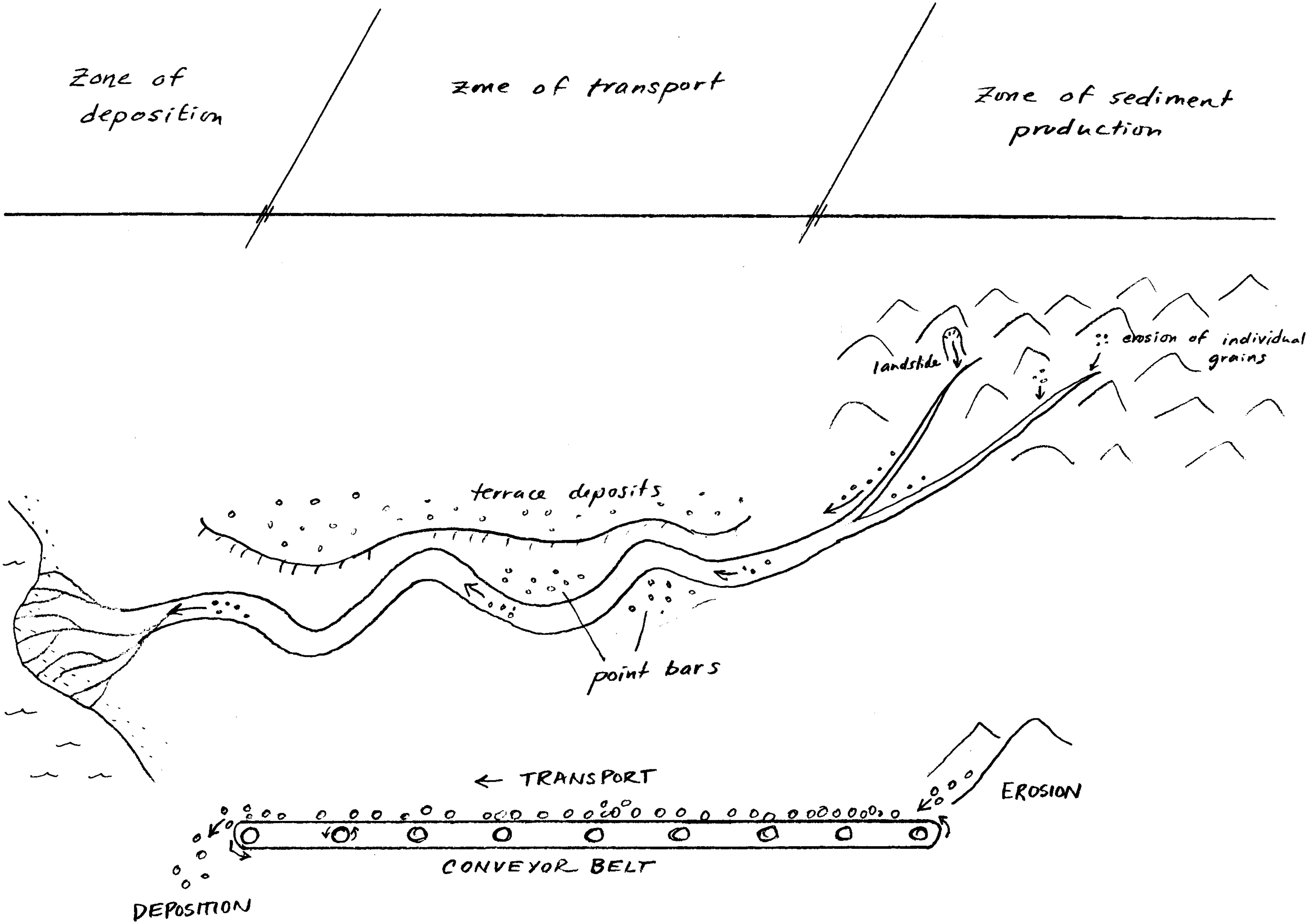


Figure 5. Diagram of zones of sediment production, transport, and deposition, and the river channel as a conveyor belt for sediment.

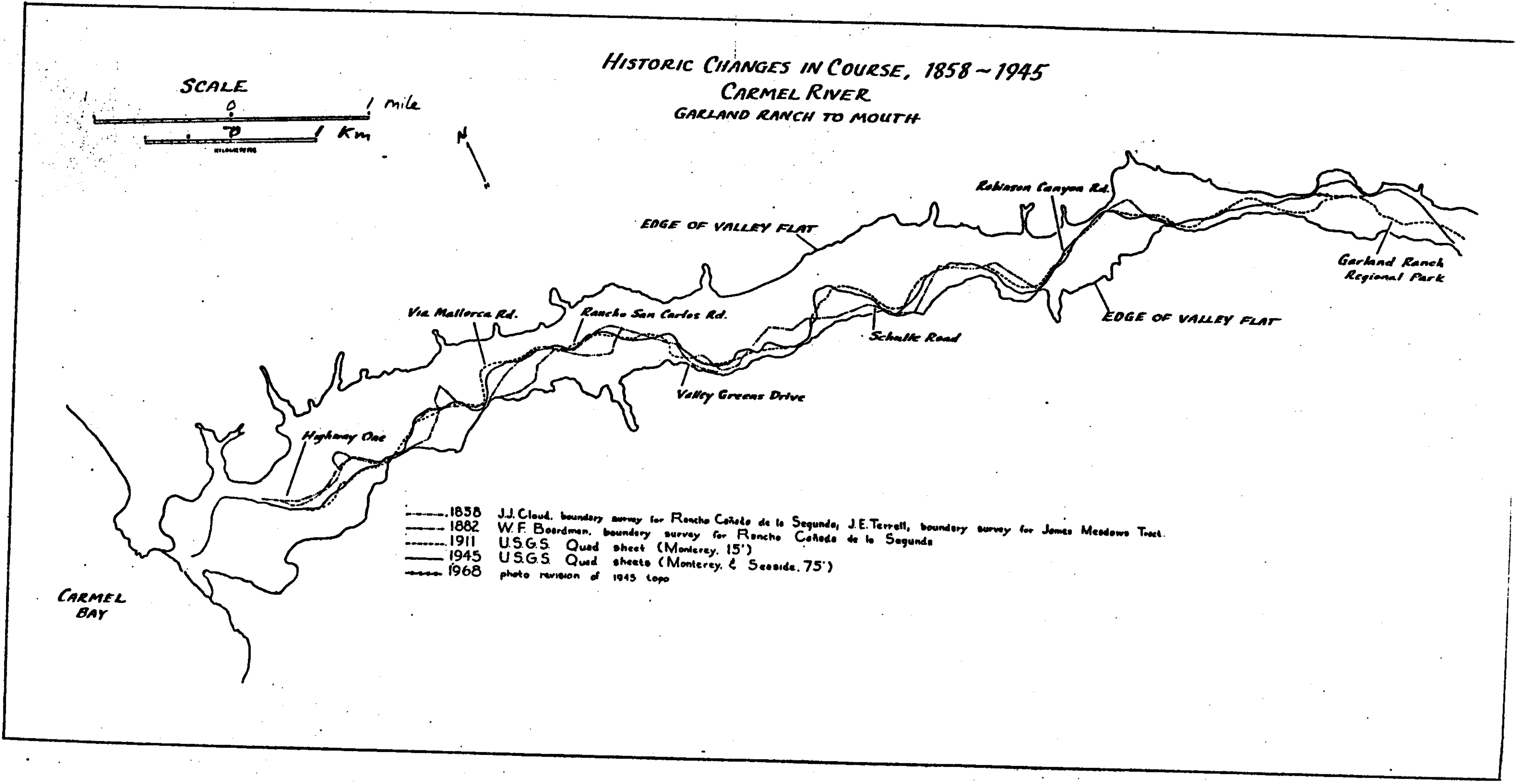


Figure 6. Channel migrations of the Carmel River, mapped from historical maps and aerial photography. (From Kondolf 1982)

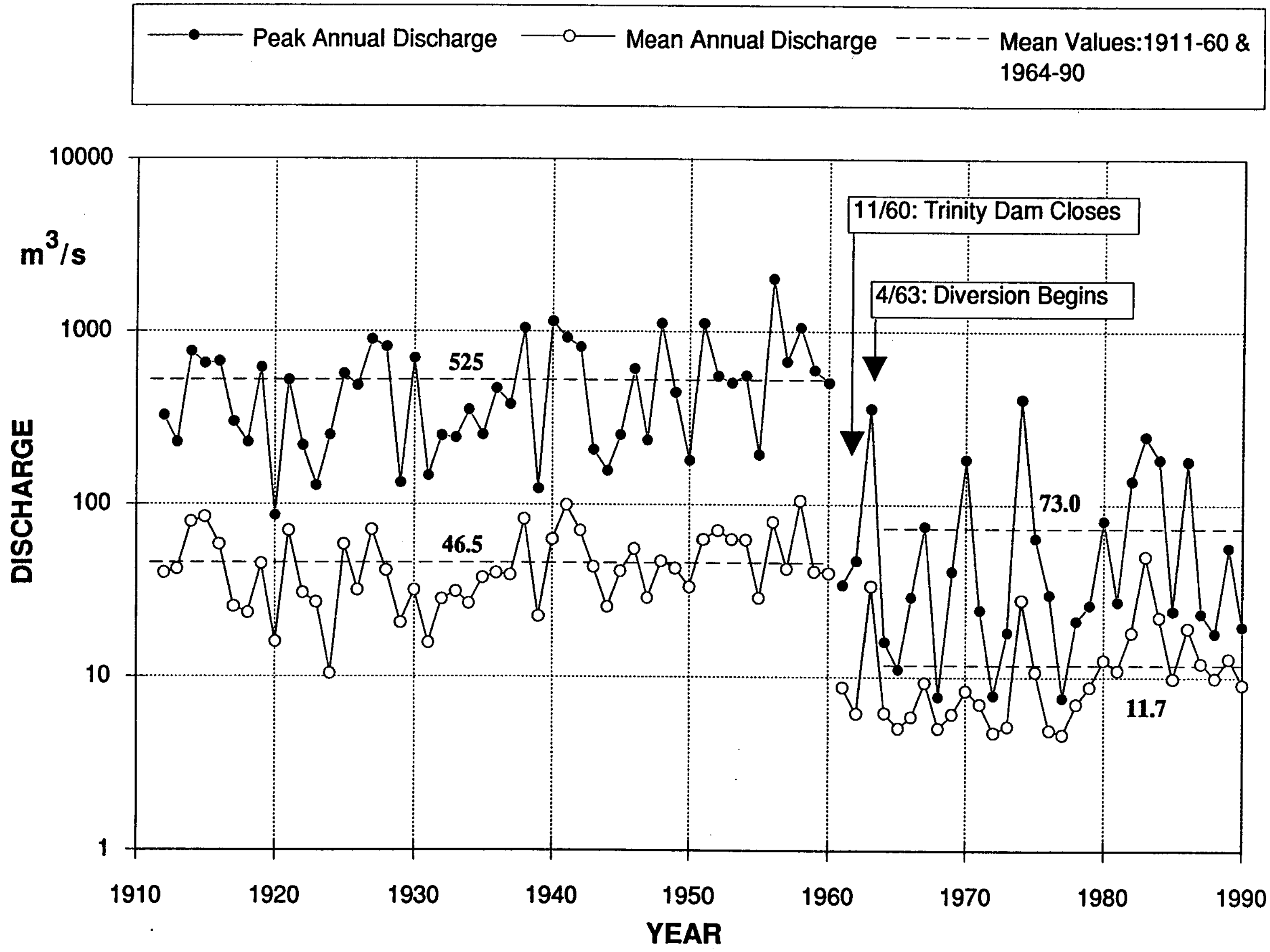


Figure 7. Annual peak and mean discharge in the Trinity River at Lewiston, 1910-1990, showing change in flow regime following closure of Trinity Dam. Ordinate is plotted in cubic meters per second (m^3s^{-1}); multiply by 35.31 to convert to cubic feet per second, cfs (ft^3s^{-1}).

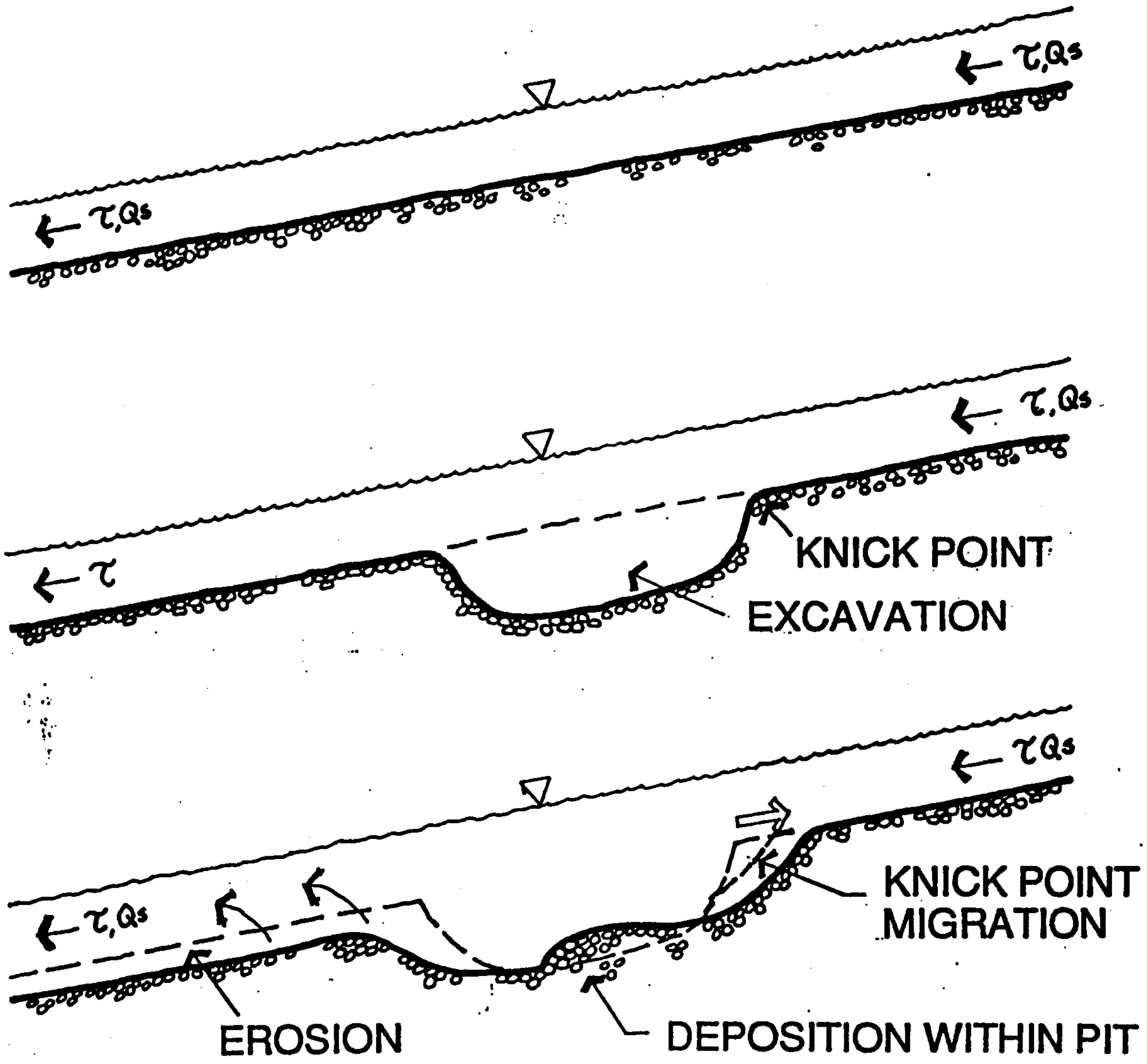


Figure 8. Effect of instream gravel pits on sediment transport and channel profile. Incision is induced upstream from knickpoint migration, downstream from erosion by hungry water.

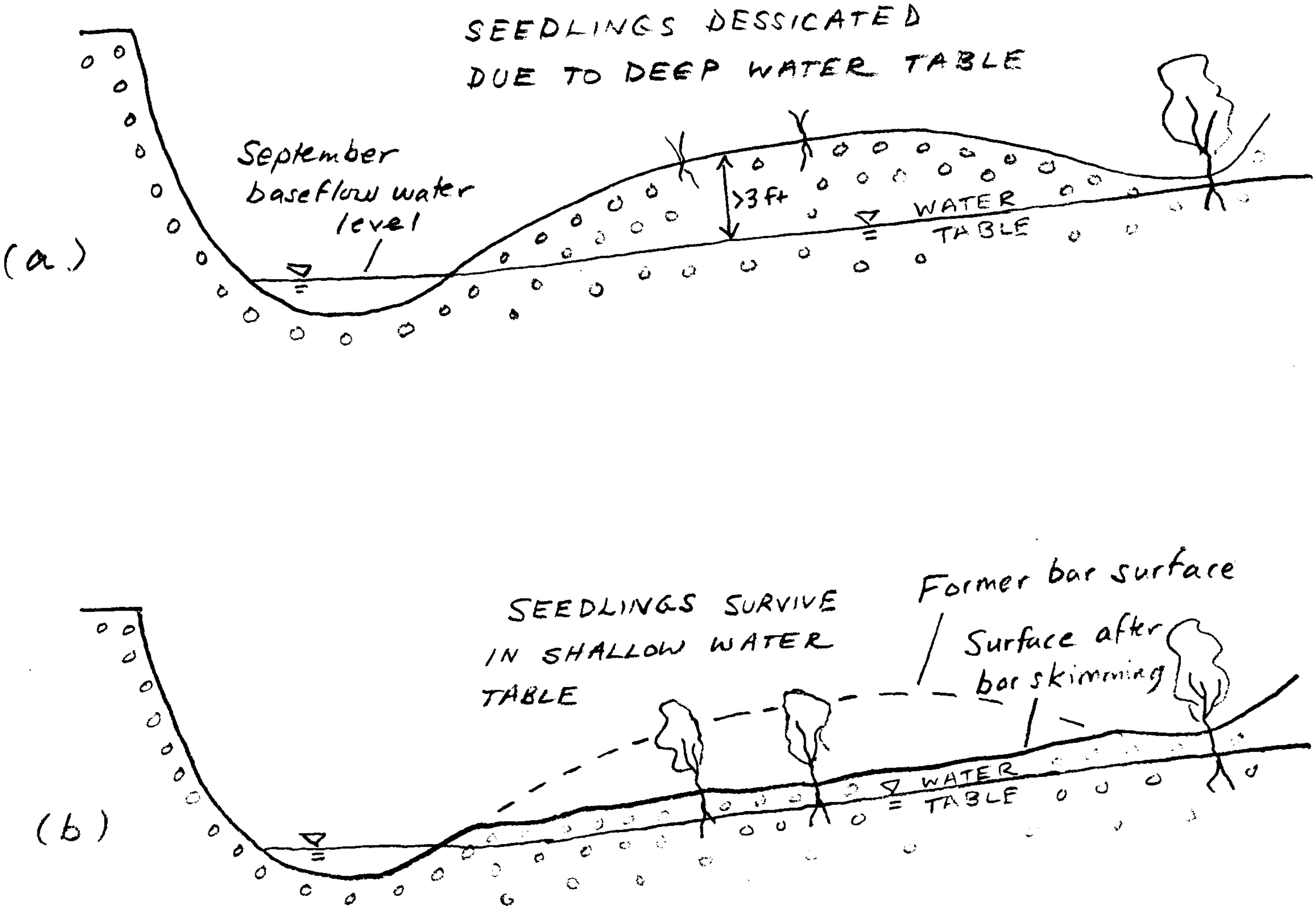


Figure 9. Diagram showing potential effect of gravel-bar skimming on establishment of willow seedlings. (a) Top of natural gravel bar is too high above late summer water table for willow survival. (b) After skimming, the surface of the gravel bar is closer to the water table, permitting survival of seedlings.

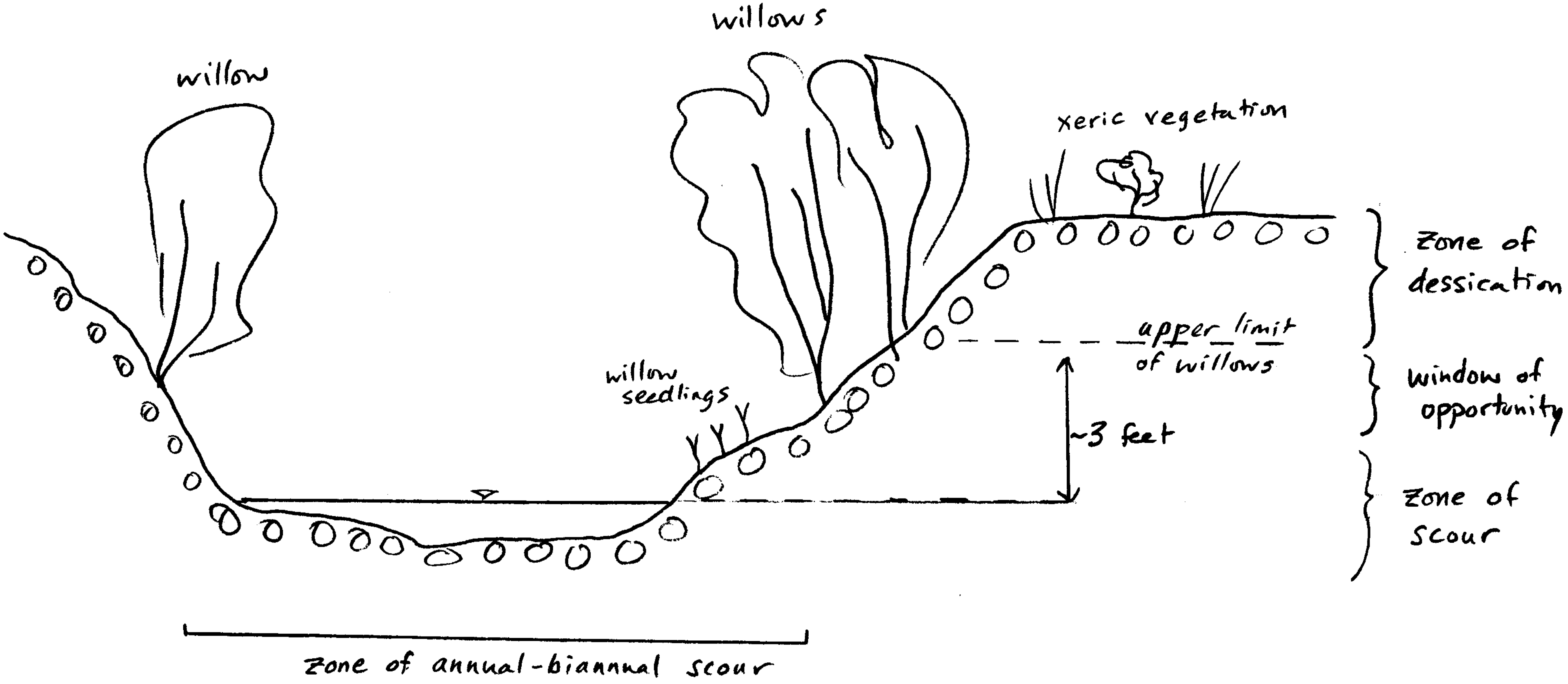


Figure 10. Diagram showing relationship between riparian vegetation establishment, height of bar surfaces above baseflow (and inferred water table level), and scour by annual or biannual floods along the Merced River at El Portal, California in the summer of 1986. (from Kondolf 1988a)

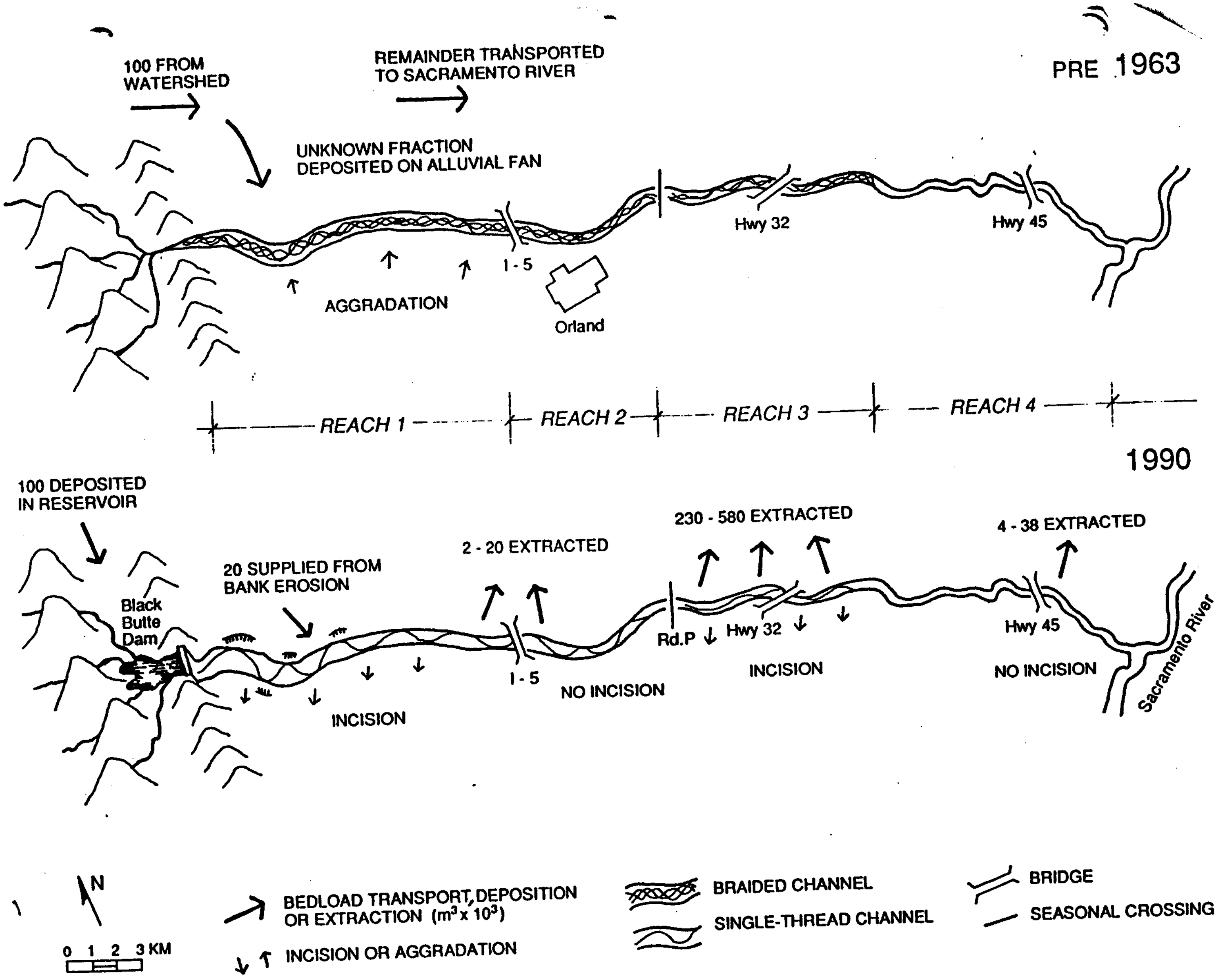


Figure 11. Sediment budget for Stony Creek below Black Butte Dam, showing pre-dam condition with supply of about 100,000 m^3yr^{-1} of gravel from the upper basin, contrasted with the post-dam situation with this supply cut off, input of about 20,000 m^3yr^{-1} from bank erosion, and extraction of large quantities of aggregate, especially near the Highway 32 bridge crossing.

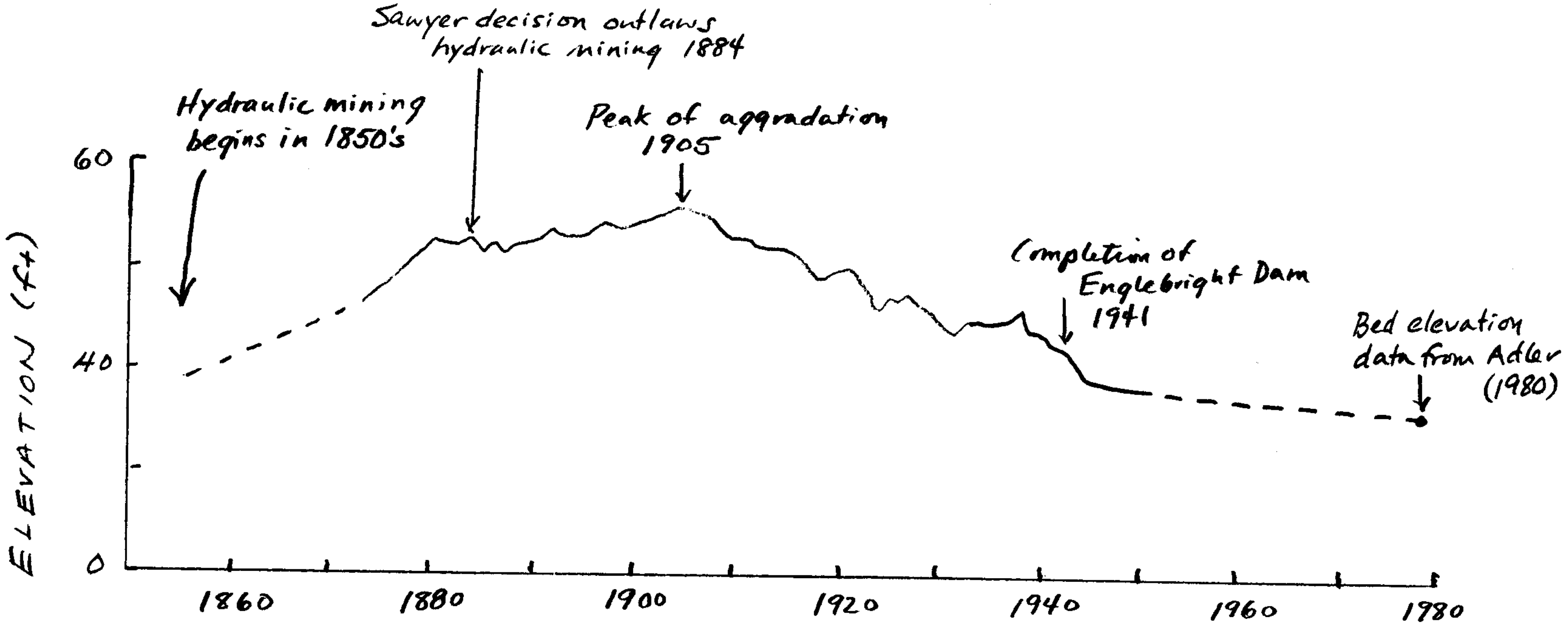
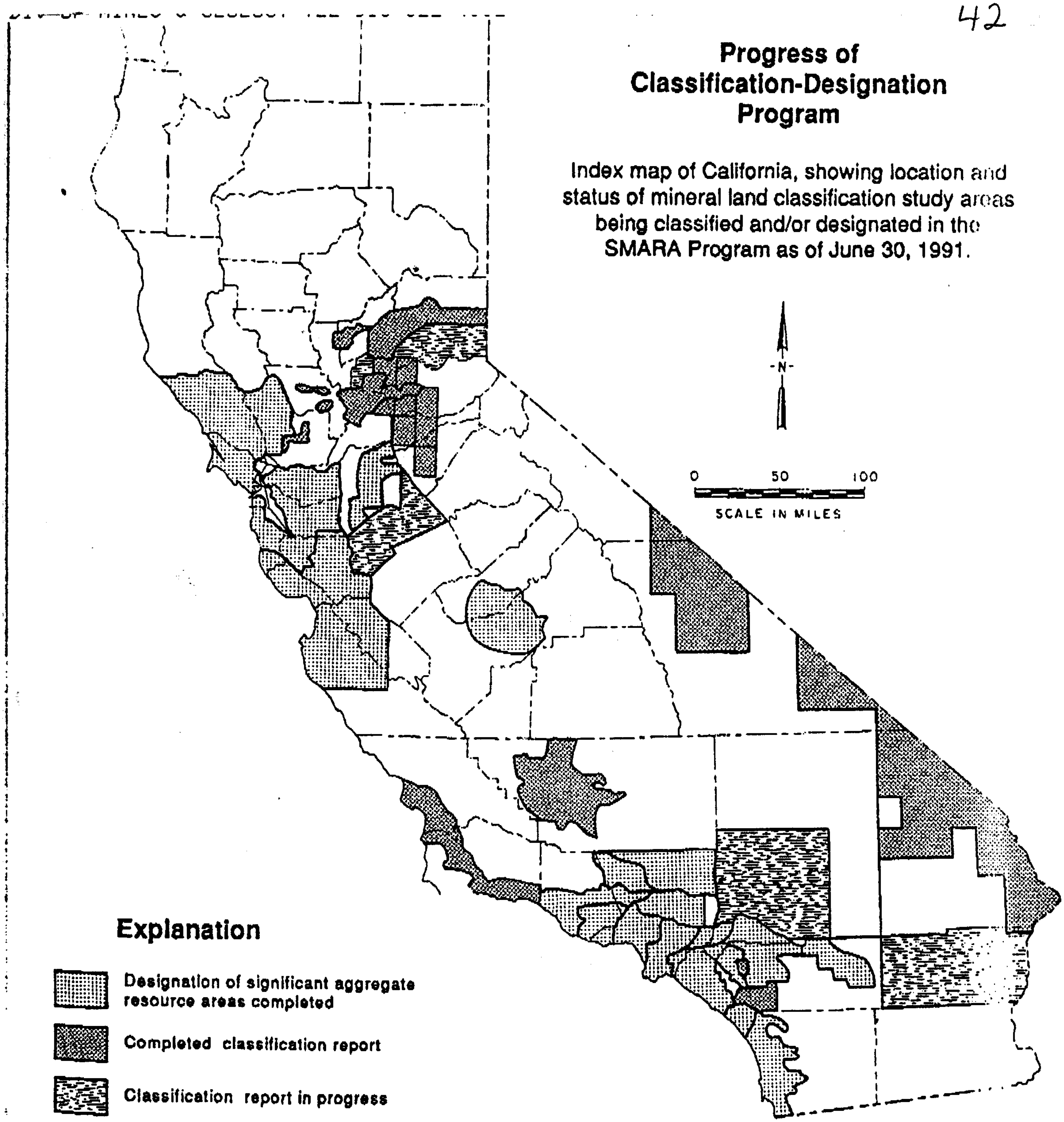


Figure 12. Change in bed elevation of the Yuba River near Marysville, 1905-1979. (adapted from Adler 1980 and Gilbert 1917)



Progress of Classification-Designation Program

Index map of California, showing location and status of mineral land classification study areas being classified and/or designated in the SMARA Program as of June 30, 1991.

Figure 13. Map depicting areas of California for which mineral land classification studies have been completed. (source: California Division of Mines and Geology, from Mining and Geology Board Annual Report for 1992.)

Table 1. Manipulation of Independent Watershed Variables by Human activities: Some Examples

Variable	CHANGE Increase	 Decrease
Flow	Flow augmentation - channel enlargement (Upper Owens River)	Reduced peak flows - channel narrowing - fine sediment not flushed from bed (Trinity River)
Sediment Load	Hydraulic mining - aggradation, recovery over decades (Yuba River)	Sediment trapped by dam - incision, bank erosion downstream (Stony Creek) - loss of spawning gravels (Sacramento River)

Table 2. Sediment Budget for the Van Duzen River Basin (from Kelsey 1980)

COMPARISON OF ACTUAL COMPUTED SEDIMENT BUDGET TO HYPOTHETICAL SEDIMENT BUDGET EXCLUDING THE EFFECTS OF THE DECEMBER 1964 STORM FOR THE VAN DUZEN BASIN, 1941–1975

	Actual sediment budget (metric tons)	Hypothetical budget without 1964 storm (metric tons)
Fluvial sediment yield from hillslopes	45,509,000	38,254,000
Landsliding		
Debris slides, debris avalanches	10,630,000	1,120,200
Earthflows	2,931,000	1,834,500
Streambank erosion		
Melange bank erosion	426,000	66,100
Flood plain and fill terrace erosion	2,619,000	131,000
Aggradation	10,601,000	none
Total sediment discharge out of basin	51,036,000	41,405,000

Table 3. Sediment Budget for the Carmel River below San Clemente Dam. (from Kondolf and Matthews 1991)

Sediment Budget for Carmel River Below San Clemente Dam. 1982 and 1983

	1982			1983		
	Suspended Load	Bed Load	Total	Suspended Load	Bed Load	Total
Output	199	118	317	1120	326	1446
Inputs						
Tributaries	13	5	18	217	39	256
Bank erosion	27	64	91	210	489	699
Total	40	69	109	427	528	955
Balance[a]	159	49	208	693	(202)[b]	491
Estimated load over dam	86	...	...	430	...	...
Unexplained balance	73	...	...	263	...	...

All values in tonnes (1 tonne equals 1000 kg). Table entries represented by three dots correspond to data categories which are not applicable.

[a] Attributed to in-channel storage changes and suspended sediment passing over San Clemente Dam.

[b] Balance is negative, indicating a net sink of bed load–sized sediment into in-channel storage.