Title

Management of Coarse Sediment in Regulated Rivers of California

Authors

Kondolf, G. Mathias
Matthews, W.V. Graham

Publication Date

1991-12-01

5/92

MANAGEMENT OF COARSE SEDIMENT IN REGULATED RIVERS OF CALIFORNIA

By
G. Mathias Kondolf
Principal Investigator

and
W.V. Graham Matthews
Research Associate

Center for Environmental Design Research
University of California
Berkeley CA 94720

TECHNICAL COMPLETION REPORT

Project No. UCAL-WRC-W-748

December 1991

University of California Water Resources Center

The research leading to this report was supported by the University of California, Water Resources Center, as part of Water Resources Center Project UCAL-WRC-W-748.

:TCR

Abstract

There are significant problems in the management of coarse sediment (sand and gravels) in regulated rivers of California. Unfortunately, these have been generally treated (or ignored) on a case-by-case basis, however, the effects are pervasive and profound, with substantial costs and severe environmental impacts. Problems arise due to the human manipulation of coarse sediment through reservoir construction, which blocks the movement of coarse sediment down the river, and through instream gravel mining, which removes this material from the river system for use primarily in construction-related projects. Impacts identified include: bed material coarsening, channel incision, channel geometry changes, hydrologic regime alterations, and changes in transport of sediment. Many of these impacts result in damage to or destruction of anadromous fisheries habitat, and are partly responsible for the dramatic declines in anadromous fisheries resources in the last 50 years. Other types of impacts include damage to instream structures, loss of riparian habitat, and increased risk of damaging channel changes.

We documented these types of impacts on a set of major river drainages on the western slope of the Sierra Nevada, along with several rivers in the Coast Ranges. We have reviewed the institutional and regulatory framework for both reservoir operation and instream mining, finding inconsistencies and lack of standard requirements for monitoring and mitigation of environmental impacts. Various techniques that comprise the existing piecemeal approach to restoration and enhancement of coarse sediment resources were inventoried. We propose alternative strategies for management of coarse sediment that incorporate planning on a system-wide (i.e. watershed) scale.

Key Words: dams, sediment transport, fisheries, fish ecology, regulatory permits, mining, reservoir management, channels

MANAGEMENT OF COARSE SEDIMENT IN REGULATED RIVERS OF CALIFORNIA

Table of Contents

List of Tables

List of Figures

Coarse Sediment Management in Regulated Rivers

INTRODUCTION

Coarse Sediment in River Systems

Coarse sediment (gravel and sand), generated by erosion in upper reaches of a watershed, is delivered to the stream network, and transported through the network predominantly by large runoff events. The coarse component of the total sediment load typically moves in rivers as bedload, by rolling, bouncing, and saltating along the bed, although in large floods and steep channels these larger materials may move in suspension (Richards 1982). Bedload commonly constitutes from 2 to 6 percent of suspended load in lowland rivers, 8 to 16 percent in mountain streams (Collins and Dunne 1990). The gravel fraction of this bedload is smaller still (and quite variable), but is of particular importance because salmon and trout depend upon gravels for spawning and incubation of their eggs. The size of gravel required for spawning varies with the size of the fish, but median diameters suitable for spawning range from about 15 mm for small trout to about 50 mm for large salmon (Kondolf 1988).

The gravel yield of a watershed depends in large part on the underlying lithology. For example, coarse grained granitic rocks commonly weather to coarse sand and granules (often referred to as "dg" for "decomposed granite"), with little gravel of sizes suitable for spawning. By contrast, volcanic lithologies commonly weather to produce suitable spawning gravels, as well as abundant suspended sediment.

Because coarse sediments constitute a small fraction of total sediment load on most rivers, because the measurement of bedload was virtually impossible until recently (Emmett 1980), and because pollutants commonly adsorb onto clays within the suspended fraction, most management-related studies of sediment have emphasized fine, suspended sediments. Suspended load is dominant especially in large rivers, which tend to have lower gradients than small rivers and streams (Richards 1982). Thus, the biggest reservoir sedimentation problems have involved deposition of fine sediment, a fact reflected in the widespread use of the term "siltation" to describe reservoir sedimentation (Mahmood 1987, Vanoni 1975).

Problem Statement

Dams interrupt the natural flow of sediment through a river system by trapping gravel and some sand. Reservoir storage capacity is lost, and the supply of gravel (needed by salmon and trout for spawning) to downstream reaches is eliminated. Dams change the flow regime, typically reducing flood peaks, in many cases depriving downstream reaches of high flows needed to flush fine sediment from spawning gravels.

Instream gravel mines operate or have operated on many rivers and streams, further reducing the supply of gravel available for spawning fish. By removing gravel from the transport system, instream mines deprive the river of its natural sediment load and can inducing downcutting, undermining bridges and other structures. Regulation of these gravel mines has proved difficult, even those operating on reaches important to spawning salmon and when the supply of gravel is known to be limiting fish population. Instream gravel mining below dams pose an especially serious threat because of the lack of replenishment from upstream reaches.

Despite the occurrence of these problems in rivers throughout the state, to date there has been no attempt to develop a coherent strategy for managing these coarse sediments in regulated rivers. It has not even been recognized as a general problem requiring a comprehensive treatment, but has been addressed only on a site-specific basis. Responses to these problems (by both dam operators and resource agencies) have been inconsistent from region to region within the state.

Coarse Sediment Management in Regulated Rivers

This study was undertaken to provide a comprehensive, planning level examination of the problem, identifying interactions among processes evident in diverse sites, and to suggest a more coherent approach in place of the presently scattered and inconsistent policies around the state.

SCOPE AND OBJECTIVES

The objectives of this research were to assess the magnitude and nature of the problem of managing coarse sediments in regulated rivers, to assess the impacts on the physical system of dam construction and instream gravel mining by compilation of basic data on hydrology, river channel, and aquatic habitat changes, to inventory and evaluate strategies currently employed by dam operators, gravel extractors, and resource agencies, and to recommend comprehensive approaches for management of coarse sediment to reduce environmental impacts and maintenance costs and to enhance existing degraded aquatic and riparian resources.

METHODS

At the outset of our study, we selected for detailed study a set of basins on the western slope of the Sierra Nevada with similar lithology, aspect, climate, vegetation, land-use, and management, from the Feather River south to the Merced River. Because of their importance for fisheries and pre-existing recognition of coarse sediment management problems, we also selected the Sacramento River below Keswick Dam and the Trinity River below Trinity Dam. For these basins, we systematically compiled hydrologic data and sought data on changes in bed material size and channel geometry. We also sought information on management strategies by reservoir operators. We were most successful in obtaining hydrologic information, but learned of little documentation of pre-dam bed material size and channel geometry, and encountered resistance to release of information on management practices such as sluicing operations. Thus, we expanded our scope to include basins elsewhere in the state for which data were available to illustrate the problems addressed in this study.

To analyze changes in flow regime induced by reservoirs, we compiled hydrologic data from the US Army Corps of Engineers (USACE), the US Geological Survey (USGS), the US Bureau of Reclamation (USBR), and regional water districts (e.g., East Bay Municipal Utilities District, EBMUD, and the Monterey Peninsula Water Management District, MPWMD). We analyzed changes in flow regime by comparing flood frequency curves for pre- and post-dam, up- versus downstream gages, or regulated versus computed natural inflow. We used existing flood frequency analyses where possible.

To measure the percentage of watersheds for which sediment yield is now trapped by reservoirs, we compiled lists of dams (under jurisdiction of the California Department of Water Resources, DWR, Division of Dam Safety, DSD) for a set of river basins selected for study. The areas above each reservoir were compiled and used in computation of unit sediment yield for the largest, downstream reservoirs. We compiled reservoir sedimentation data from operating agencies and published sources, adjusting these values for upstream impoundments.

To document channel response to upstream reservoir construction and operation, and to instream gravel mining, we compiled data on bed degradation and changes in bed material size. Bed degradation data were compiled from previous field work by the authors, from discharge measurement notes at USGS gages, and from bridge maintenance files at the California Department of Transportation in Sacramento. Bed coarsening below dams was more difficult to document because data on bed material size prior to dam construction was generally not obtainable; in some cases we inferred approximate pre-dam gravel sizes based on observed spawning activity. We collected data on current bed material sizes from reconnaissance-level field work, from agency reports, and from unpublished data and observations by agency personnel.

We compiled data on problems of fine sediment accumulation in gravels below dams from published sources, agency and consultant reports, and discussions with agency personnel.

We interviewed dam operators and resource agency personnel regarding policies on coarse sediment management, such as sluicing of small diversion structures. We compiled information on gravel enhancement projects (volumes and costs) from agency personnel, agency reports, and unpublished data. Costs of other mitigation measures, such as flushing flows and removal of sediments accumulated in reservoirs, were also compiled.

To document the degree to which instream gravel mining is now regulated and monitored, we conducted telephone interviews with all county-level lead agencies to learn of the extent of instream mining in the jurisdictions, and any strategies used to monitor and evaluate the excavations and compliance with reclamation plans.

Based on results of the above studies, we developed recommended strategies for management of coarse sediment that recognize the interactions among the effects of diverse activities and attempt to view the problems in a basin-wide context.

GENERAL EFFECTS OF RESERVOIR CONSTRUCTION AND OPERATION

Although dams are constructed and operated for a wide variety of purposes including water supply (residential, commercial, and agricultural), flood and/or debris control, and hydropower production, they share many of the same effects on their river systems. All dams trap sediment to some degree, and most alter the flood peaks and seasonal distribution of flows.

Coarse Sediment Management in Regulated Rivers

At this point it is useful to distinguish the effects of small diversion dams (common in the Sierra Nevada but frequently overlooked) from the effects of larger dams. Most of the following discussion applies primarily to larger dams, but in this study we have also considered management of the small diversion structures, which have relatively little effect in modifying flood peaks and limited capacity to store sediment, but to maintain operational integrity, sediments must be mechanically removed or sluiced from them. Sluicing can alter the timing of delivery of sediment to downstream reaches.

Reservoir Sedimentation.

Dams interrupt the flux of sediment through the river system. As a result, reservoirs trap all of a river's bedload and a portion of the suspended load that depends upon the ratio of inflow to capacity (Brune 1953). Large reservoirs such as Clair Engle Lake on the Trinity River have trap efficiencies of essentially 100%, while small reservoirs like San Clemente (on the Carmel River) have trap efficiencies as low as 21% (estimated at 60% after closure, since reduced by sedimentation)(Matthews 1988). Small diversion ponds may fill with sediment in a single wet year, as occurred behind Log Cabin Dam on Oregon Creek, Our House Dam (also listed as "Hour House") on the Middle Yuba River, and other such structures in 1986.

In most cases, reservoir sedimentation is an undesirable byproduct of reservoir construction and operation. In some cases, however, reservoirs have been constructed specifically to trap sediment. One such dam was completed last year on Grass Valley Creek, a tributary to the Trinity River below Lewiston Dam, to reduce the tributary's sediment input to the mainstem (D. Denton, DWR, personal communication 1991).

More massive projects were undertaken in the Sierra Nevada under the California Debris Commission through 1940. A number of "debris dams" were constructed for the purpose of trapping sediment introduced by hydraulic mining, thereby isolating the effects of hydraulic mining from urban and agricultural areas downstream (Yeend 1974). Englebright Dam was constructed as a debris dam but was subsequently retrofitted for hydropower production. In some other cases, debris dams have been abandoned. An example is the debris dam on Slate Creek in the North Yuba watershed about 0.5 miles upstream of the Oroville-Wyandotte Irrigation District (OWID) diversion structure, which filled with sediment (largely gravel) and was illegally dynamited in the 1960's by placer miners seeking to liberate the gravel stored behind it. The dam now has a large crack through which sediment stored in backwater deposits upstream is metered out at flood stage, creating sediment problems for the OWID diversion structure downstream. No agency is willing to take steps to address this problem because none wishes to become responsible for the dam and its safety (Kondolf 1986).

Reservoir Filling with Sediment.

Ultimately, all reservoirs can be expected to fill with sediment. If current sedimentation rates (presented below) are projected into the future, most large reservoirs have lifetimes of a century of more. However, sedimentation rates will increase if sediment yields from the watershed increase, as may occur from changes in land use.

Many small reservoirs have already largely or completely filled with sediment, such as the small impoundments behind PG&E diversion dams (discussed below). Another example is the former Sweasey Dam on the Mad River near Arcata, which filled rapidly with sediment and was removed in 1970; sediment stored in the reservoir was transported downstream in subsequent high-flow years (R. Kiah, Caltrans, personal communication 1991). Unfortunately, the downstream migration of this sediment (as a pulse or dispersed) was not well documented. Since 1970, the mouth of the Mad River has migrated northward, threatening Highway 101, but it is not clear whether this effect was due to release of sediment from Sweasey Dam, from instream mining, or other causes (G. Heise, CDFG, personal communication 1991).

A dam on Malibu Creek has completely filled with sediment, and there is interest in having the dam removed among local groups and the California Department of Parks and Recreation (CDPR), which now owns the site. The dams blocks upstream migration for the southernmost remnant run of steelhead trout in California. However, the cost and logistical difficulties of operating within the confines of the canyon, as well as liability for possible downstream impacts, has prevented any such action to date (T. Taylor, CDPR, personal communication 1989).

Once a reservoir fills with sediment, most of its original functions are lost: water storage for water supply, flood control, etc. In cases of small diversion dams, water storage is not an issue, but if sediment fills the reservoir to the intake level, bedload may be transported into tunnel or penstock intakes, potentially damaging structures. Moreover, DSD regulations require that low-level outlets be operable so that reservoirs can be drawn down in emergency situations (DSD 1991). Low-level outlets are rendered inoperable in reservoirs completely filled with sediment. Maintenance of low-level outlets appears to be a principal reason for sediment removal from small diversion dams. Many older dams are not equipped with low-level outlets, and thus have no such requirement.

Once sediment has completely filled-in behind a small diversion dam, bedload can pass over the top of the structure, and the dam no longer interrupts the natural flux of sediment through the river system. The dam simply acts like a large waterfall. It may block fish passage and have other effects, but it no longer interrupts the continuity of sediment transport.

One aspect of this problem appears to have been unaddressed in the literature: the potential for dam failure resulting from transport of bedload through outlet works. Bedload should have a greater potential for abrasion and erosion than clear water, potentially increasing the risk of damage to the dam and its ability to pass large floods safely. We have examined some small concrete-arch diversion dams in the Sierra over which bedload was transported, at least in the February 1986 event, and we detected no evidence of accelerated spillway abrasion. It is probable that earthen dams would be more vulnerable to failure in this fashion because destruction of the spillway could potentially expose readily entrained sediment constituted the bulk of the structure. The potential for increased abrasion and risk of structural damage is an engineering question for which we do not possess expertise. However, it remains unclear to us whether this potential hazard is, in fact, not serious, or whether there has been no encouragement within engineering community to raise such an uncomfortable question.

Another curious aspect of the reservoir filling problem is that once the reservoir has completely filled, its capacity falls under the 15 ac-ft minimum size for jurisdiction by DSD. The Malibu Creek reservoir is an example (D. Babbitt, DSD, personal communication 1991). It is unclear whether this loophole would apply only to older structures not equipped with low-level outlets, or if it would apply to any reservoir that completely filled.

Once a reservoir has filled with sediment, it can be left as is (trusting that abrasion will not destabilize the dam outlet works), the sediment behind it could be removed, or the dam could be removed. Removal of sediment from small reservoirs can cost upwards of $100 per cubic foot, depending upon access and distance to a disposal site (E. Stassevich, PG&E Hydro-Generation, San Francisco, personal communication 1987). As discussed below, the potential for exploitation of these sediments as aggregate has been inadequately explored in most parts of the state. As pollutants have been termed "resources out of place" (Miller 1990), so the coarse sediments accumulated in reservoirs can be viewed as potential sources of aggregate.

Removal of dams completely filled with sediment can result in catastrophically increased delivery of sediment to downstream reaches, potentially overwhelming the channel, resulting in aggradation and destabilization. The change in sediment load would not be fully apparent until the first high flow following dam removal. Thus, several years could pass before the newly available sediment migrated to downstream reaches.

In the case of concrete dams, it may be possible to remove them in stages, so that the sediment could be metered out to downstream reaches, reducing the risk of catastrophic channel change. In the case of earthen dams, however, no such option exists. Once the hardened superstructure was removed, the earthen material constituting most of the dam would be readily entrained by high flows and dam would be rapidly destroyed, much as occurred with the Auburn cofferdam in February 1986.

Downstream Coarsening and Incision.

While a review of the relevant geomorphic and hydrologic literature shows a proliferation of reports on the physical characteristics of the channel downstream that have been altered by dam construction in the last two or three decades, it is only in the last ten years that information on the ecological consequences of these changes has become available. The physical effects described in the literature include bed degradation or incision, bed coarsening or armoring, decreased sediment transport of downstream tributary derived materials, tributary incision, changes in channel geometry and capacity, and encroachment of riparian vegetation. (In this study, we use the terms bed "degradation" and "incision" synonymously.) These changes induced by dam construction and reservoir operation are the result of the interruption of the movement of sediments through the river system and alteration of the pre-dam flow regime. The chart in Figure 2 links these direct effects of dams with the physical changes which result and finally the ecological impacts downstream. The following paragraphs describe these changes and their associated impacts in more detail.

Channel degradation is generally observed below dams because the reservoirs commonly trap all of the bedload and a substantial portion of the suspended load derived from the upstream watershed and release clear water. This water is often termed "hungry" water because it possesses stream power greatly in excess of its reduced sediment load and is often sufficiently capable of eroding its bed and banks in an effort to regain its "equilibrium" sediment load. Incision below dams is most pronounced in rivers with fine-grained bed materials and in those which have lesser impacts on flood peaks (Williams and Wolman 1984). In gravel-bed rivers, a stable, coarse surface layer is typically observed to develop (the process is often called "armoring") below reservoirs as finer materials are winnowed downstream by the hungry water (Williams and Wolman 1984). This armor layer will continue to develop and coarsen until the material is no longer capable of being moved by the reservoir releases or spills. The magnitude of bed degradation depends upon the reservoir operation, channel characteristics, and the sequence of flood events following dam closure. For example, up to 6 meters of bed degradation have been observed on the Colorado River below Davis Dam (Williams and Wolman 1984) and numerous other examples of channel downcutting in the 1-3 meter range are presented in Williams and Wolman (1984) and Petts (1984). Examples of armor layer development are described by Borland and Miller (1960), Harrison (1950), and Williams and Wolman (1984).

The ecological impacts from this bed coarsening are primarily centered around changes to, and loss of, aquatic habitat for anadromous fisheries. In many cases, the channel bed coarsens to such an extent that the fish are no longer able to create spawning nests, or redds. In extreme cases, virtually all of the alluvial material is removed and only boulders and bedrock remain.

The availability of spawning gravels can also be reduced below dams as a result of channel incision, in which formerly submerged gravel beds are isolated as terrace or floodplain deposits and from elimination of gravel recruitment from bank erosion as encroaching vegetation stabilizes banks (e.g., Hazel et al. 1976, p.496).

Changes in Sediment Transport Downstream

Decreased sediment transport below reservoirs has been documented in many rivers (Williams and Wolman 1984) due to the sediment trapping ability of the reservoirs, and the sediment load of most of these rivers does not recover to the rate upstream of the reservoir despite downstream tributary contributions. The combination of flow regulation and sediment trapping by reservoirs substantially reduces the amount of sediment available for beach replenishment. Further upstream, both the capacity and competence of the river in terms of sediment transport is reduced due to changes in flow regime, and in many cases, streamflow is not capable of flushing tributary-derived sediments through the mainstem. Tributary sediment delivery rates may be accelerated by land use changes or by incision of the tributary channel as a result of the desynchronization of tributary and mainstem peak flows due to lags from reservoir storage effects, or through base level lowering from streambed degradation in the mainstem. The impact of tributary sediment loads in excess of the mainstem's ability to transport them lies in the deposition of fine sediments, generally sand-sized material, in remaining spawning gravels, if any, which will further reduce spawning success. Examples of these effects are described in King (1961), Hathaway (1948), Warner (1981), Kellerhals and Gill (1973), Petts (1984), and Williams and Wolman (1984).

Channel Geometry Changes

Changes to downstream channel geometry are caused by the bed degradation and due to a reduction in the frequency and magnitude of flood scour from regulation which permits riparian vegetation to encroach into the active channel. While variations exist due to differing reservoir operations, in many rivers the channel geometry adjusts to a shape in equilibrium with the post-dam dominant discharge. Unfortunately, most of the documentation of reported changes are not accompanied by data on the change in flow regime that produced the channel adjustment (Petts 1984, Gregory 1987). Increases in width are typically found below reservoirs operated for hydroelectric power generation, in which rapid changes in stage are common and the channel contains water most of the time. Channels that experience low flows during much of the year tend to experience decreases in width through the encroachment of vegetation and deposition of sediments along the channel margins as a result of the increased hydraulic roughness from the vegetation (Williams and Wolman 1984). While the encroachment of vegetation produces certain positive habitat values, such as cover and shading of the stream channel, in many cases, the channel becomes too uniform and, with the absence of large flood peaks, so stable that the natural diversity caused by a certain amount of bank erosion and channel migration is eliminated.

Coarse Sediment Management in Regulated Rivers

The regulation of rivers through dam construction has produced many beneficial results for society, although the environmental costs of these benefits have all too frequently been overlooked. By understanding the effects caused by this regulation, it is possible to develop management techniques that may be able to partially mitigate these impacts.

GENERAL EFFECTS OF INSTREAM GRAVEL MINING

Demand for Aggregate from Active Streambeds

Instream gravel mining is the other significant human activity that affects the movement of coarse sediment through a river system. 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. River sediments are typically of excellent quality because natural river processes eliminate weak materials by abrasion and attrition, and the resulting deposits are durable, rounded, well-sorted, and relatively free of interstitial fine sediment.

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). This amount is almost double the estimated production of 65,000,000 tons in 1955.

The aggregate available from active riverbeds is especially desirable because it requires little processing (having been washed by fluvial processes) and, commonly, little transportation because suitable stream gravel deposits are typically located near the markets for the product. Transportation costs are especially important to the industry, because the material itself is essentially free except for processing. A rule-of-thumb is that the cost of the product doubles with each 25 miles of transport (Randy Sater, Teichert Construction Company, personal communication 1991).

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 (in which interstitial fine sediment content is often greater, requiring additional processing), quarries (from which rock must be crushed, washed, and sorted), or distant sources, such as reservoir deltas, involving greater transportation costs.

In this study, we define five types of mining of gravel within the channel and floodplain: dry-pit and wet-pit mining in the active channel, bar skimming, and dry-pit and wet-pit mining on the floodplain. In-channel pit mining involves excavation of a pit below the thalweg (lowest point in the stream cross section). Dry-pit refers to pits excavated on dry ephemeral stream beds with conventional bulldozers, scrapers, and loaders; wet-pit requires use of a dragline or hydraulic excavator to extract gravel from below the water table level or in the stream itself. Bar skimming refers to scraping of the top layer (of variable thickness) from a gravel bar without excavating below the summer water level. Floodplain pit mining refers to excavation of pits on the current floodplain or adjacent river terraces. In some cases these pits are constructed adjacent to the active channel, separated only by a small levee.

The first three types of mining are clearly operations in the active channel and are defined as instream gravel mining in this study. Floodplain mining, on the other hand, is isolated from the active channel, at least in the short term. However, it is likely that during major floods these floodplain operations may become part of the active channel through bank erosion and/or channel avulsion, and is considered potentially instream. The risk of channel changes is greatly reduced where large upstream reservoirs are able to completely control even floods as large as the 100-year flood. In these cases, floodplain mining could be considered geomorphically distinct in the near term. Terrace mining that is geomorphically distinct from the active floodplain falls in another category and is not directly considered in this study.

Depending on the type and amount of mining, the physical effects of sand and gravel extraction range from beneficial flood control and channel stability enhancement through control of channel aggradation (Griffiths 1979), a situation uncommon in California at present, to the destruction of aquatic and riparian habitat through large changes in channel morphology (Woodward-Clyde Consultants 1976). Impacts described in the literature include: bed degradation, bed coarsening, lowered alluvial water tables, and channel instability. These physical impacts result in degradation of riparian and aquatic ecology, and in undermining of bridges and other structures (Figure 3).

Incision Produced by Instream Mining

As noted above, the sediment in the bed of rivers is not a static feature, but is a dynamic feature, in transit through the system during floods. The flux of bed sediment depends on the supply of coarse sediment from the watershed and the transporting power of the river, and transport rates vary over space and time. The size and shape of the stream channel reflects its prevailing flow and sediment load (Leopold et al. 1964). If the sediment flux is altered, the river channel is likely to adjust to the changed conditions. Instream gravel mining, by removing sediment from this continuum, disrupts the preexisting balance between sediment supply and transporting power.

The concept of "replenishment rate" is commonly applied to instream gravel mining to specify acceptable levels of sustained yield. 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 essentially the creation of hungry water downstream of extraction sites, and the river will typically 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."

The most dramatic effects of instream mining occur when pit mining is conducted within the active channel. By excavating large pits, whether shallow or deep, the "equilibrium" profile of the streambed is altered and the channel must adjust to the locally steeper gradient upon entering the pit (Figure 4). This steeper gradient creates a stream power excess which is generally capable of eroding the bed. This process is known as "headcutting" or "knickpoint migration", and the effects may translate upstream for considerable distances. Continued extraction may cause the entire streambed to degrade to the depth of excavation. As the streambed degrades, the material remaining on the surface will coarsen as the finer material is more easily transported leaving a coarse lag, and an armor layer similar to that seen downstream of dams forms. In severe cases, the degradation will continue until bedrock or older substrates under the recent alluvium are uncovered. Pit excavation will also induce bed degradation downstream, because much of the incoming sediment load will be trapped in the backwater created by the pit "reservoir", and relatively clear water will exit the downstream end of the pit.

Gravel bar skimming withdraws sediment from the transport system and thus alters supply to downstream reaches, but the volumes removed are typically less than pit mining. Gravel bar skimming, even when rates are less than "replenishment", can have a profound impact on channel geometry by creating a wide flat cross section that changes the channel hydraulics, eliminating channel confinement and removing the "pavement," the coarse surface layer than occurs on many natural river beds and appears to regulate rates of bedload transport. When rates are in excess of replenishment, bed coarsening and degradation may occur downstream, and these effects can propagate upstream much as the knickpoint created by pit mining (Matthews and Associates 1991). Another impact of pavement removal is exposure of finer subsurface material to entrainment at low flows; this fine sediment may be transported downstream to be deposited in gravels and in pools (Matthews and Associates 1991).

Incision has many direct effects, notably the undermining of bridge piers and other structures. The cost of such damage to bridges through 1984 in the state probably exceeded $12 million, as discussed below. Degradation can induced 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 impacts riparian and aquatic habitat by loss of temperature moderating effects of shade and cover, and habitat diversity. As noted in the section on reservoir impacts, bed coarsening results in loss of spawning gravels for salmonids. Extensive degradation may induce a decline in the alluvial water table, as the banks are effectively drained to a lowered level. Lowered water tables have affected riparian vegetation and water supply wells (Woodward-Clyde Consultants 1976).

By eliminating channel confinement, gravel bar skimming reduces habitat diversity, resulting in a wide, shallow channel lacking in the pools and cover needed by fish, and potentially increased water temperatures.

By virtue of its removal from the active channel, terrace-pit mining (wet and dry) generally does not impact coarse sediment flux in the channel. However, many of these pits are separated from the active channel only by levees; in some rivers, these levees have been breached during floods, and the channel has avulsed or migrated into the pits, resulting in an unstable, chaotic channel configuration.

RESERVOIR EFFECTS IN CALIFORNIA

Density of Reservoirs in California

California rivers are highly regulated. Among the state's large rivers, only the Smith remains unregulated. Many west-slope Sierran drainages are now a staircase of dams and reservoirs, with flow largely routed through tunnels and canals for power production. There are 1212 dams regulated by the California Department of Water Resources Division of Safety of Dams (DSD) and another 144 dams operated by the federal government within California (DWR 1988).

There are many small dams that are considered too small to be regulated and are not included in these figures: dams that 1) are less than 25 ft in height and that impound less than 50 ac-ft, or 2) are less than 6 ft in height regardless of size of impoundment, or 3) impound less than 15 ac-ft regardless of height (DWR 1988). Although DSD maintains no listing of non-jurisdictional dams, they could be identified from records in the Division of Water Rights. The number of these smaller, non-jurisdictional dams is suggested by the change in the number of jurisdictional dams that accompanied a relaxing of the jurisdictional size in the 1930's. The original legislation establishing state regulation of dam safety, passed in 1929 in the aftermath of the Saint Francis Dam failure, required that the state regulate dams greater than 15 ft in height, 30 ac-ft in capacity. The jurisdictional size was increased to the present 25-ft height and 50-ac-ft capacity during the depression to reduce costs. This action cut the number of jurisdictional dams roughly in half (D. Babbitt, DSD personal communication 1991).

For the central west-slope Sierra, our inventory of dams is presented in Table 2. In addition to DSD-regulated dams, this table includes a listing of smaller structures operated by Pacific Gas and Electric Company (PG&E) (PG&E unpublished data). Non-DSD dams operated by other agencies are not included in this tabulation but may be numerous. In the highly regulated Stanislaus River basin, there are 40 dams upstream of the major downstream dam. We present detailed tabulations of upstream dams in five of these central west-slope basins in Tables 3-7.

Despite their numbers, these smaller upstream dams are dwarfed in effect by the large downstream reservoirs located in the foothills. For example, in the Stanislaus River system, the 40 upstream dams account for only 16% of the total basin impoundment; the major downstream dam, New Melones, impounds 84%. In many cases, dams were located at or near these downstream sites early in the century, but the dams were enlarged in the 1960's or 1970's (Table 2).

Upstream Dams

The smaller upstream dams are typically operated very differently from the major downstream projects. Many of the small structures are diversion dams without significant storage (and commonly smaller than DSD-jurisdictional size) that serve only to provide favorable conditions for operation of tunnel intakes (e.g., Log Cabin Dam on Oregon Creek). Many of these structures are part of high-head hydroelectric projects and operate in a "run-of-the-river" mode, that is without enough storage to affect the seasonal distribution of flows. However, by virtue of nearly constant diversions from the river, they have a proportionally greater impact on low flows.

In other cases, upstream dams have enough storage to significantly affect the seasonal distribution of flows. An example is the New Spicer Meadows Dam in the Stanislaus River basin (Table 6). This reservoir stores snowmelt (and rain-on-snow) runoff for gradual release through the summer, resulting in an anticipated 10-fold increase in summer base flows in much of the North Fork Stanislaus River (Calaveras County Water District 1985).

There is little consumptive use of water from the upstream impoundments. Mostly, water is stored seasonally or shifted to adjacent drainages. Some upstream reservoirs may store water seasonally, but typically do not have capacity for significant interannual storage. There are numerous interbasin diversions in west-slope Sierran drainages, typically to maximize power generation. For example, Slate Creek in the North Yuba drainage is dammed and diverted via tunnel into the South Fork Feather system. Another example is the Middle Yuba, which is diverted at Our House Dam via tunnel into Oregon Creek, and thence via tunnel into the North Yuba River to augment storage in New Bullards Bar Reservoir. (The Yuba River system is unusual in that the downstream-most reservoir is not the largest reservoir. Englebright Dam was built to trap debris from hydraulic mining with 70,000 ac-ft capacity; upstream on the North Yuba, New Bullards Bar has 969,000 ac-ft capacity.)

The upstream dams are also distinctive in the fish resources they affect: resident trout and non-game species. Anadromous salmonids cannot migrate past the downstream dams, so the fish resources are limited to resident populations, which by nature are smaller and require less suitable spawning gravel to naturally maintain themselves.

The upstream dams, by virtue of their smaller capacities, are more vulnerable to filling by sediment, but it is also easier to remove sediment from them mechanically or by sluicing, as discussed below.

Major Downstream Dams

The large dams, commonly located in the foothills, have effected massive changes upon the hydrology, sediment transport, and aquatic ecology of west-slope Sierran rivers. The nature of these hydrologic changes is discussed below. The large dams also trap all bedload and most suspended load, depriving downstream reaches of upstream gravel supply. As a result, spawning gravels may be progressively lost from the system, with recruitment of new gravels limited to bank erosion and tributary contributions. As discussed above, incision is common below these dams.

The most significant ecological effect of these dams has probably been prevention of anadromous salmonids from reaching their natal spawning grounds. This single effect has been devastating to salmonid populations throughout western North America, resulting in the extinction of numerous races adapted to specific drainages. Now that anadromous salmonids are limited to spawning in reaches downstream of the major dams (and in a few unobstructed tributaries), the next most important impact is the alteration of flow magnitude, timing, and temperature, as well as loss of young fish to diversions (Hallock 1987, CACSST 1988, USRFRHAC 1989). For example, because of storage of snowmelt runoff by Shasta Dam and effects of heated irrigation return flow, the mainstem Sacramento River may reach temperatures lethal to salmon smolts by the end of May, so only smolts that leave early can outmigrate successfully. The rest (probably a majority) successfully follow tributaries (such as the American) to the Sacramento confluence, where they are killed by thermal shock (F. Meyer, CDFG, personal communication 1991).

As we discuss other effects of these large dams, it is well to keep in mind that anadromous salmonid populations are most urgently threatened by flow reductions, cut-off of upstream spawning grounds, and commercial harvesting offshore. However, the sediment-related problems we discuss here are important, and will assume greater importance if these more urgent threats to the fish are resolved.

Reservoir Sedimentation

Data on reservoir sedimentation rates were surprisingly rare in recent decades. In general, large reservoirs have not been resurveyed since the 1940's, presumably because of budget limitations and confidence in the adequacy of reservoir capacity which allowed for sedimentation in the reservoir design and sizing. Smaller reservoirs such as the Carmel River reservoirs have been surveyed more frequently, probably because lifetimes of these reservoirs are shorter and because of the increasing demand for the water resources from the growing communities that depend upon them. Many large reservoirs have not been surveyed in recent years, including Pardee and Camanche reservoirs on the Mokelumne, which have not been surveyed since 1943 (T. Linville, EBMUD, personal communication 1991); Folsom reservoir on the American (J. Maglinte, USBR, personal communication 1991); Soulajoule, Nicasio, and Kent reservoirs in Marin County, which have never been resurveyed (R. Arena, MMWD, personal communication 1991); Calaveras and San

Antonio reservoirs in Alameda County, which have never been resurveyed (E. Stewart, SFWD, personal communication 1991).

Table 8 presents reservoir sedimentation data provided to us by operating agencies or drawn from older surveys for Sierran watersheds, where sediment yields are typically 0.1-0.4 ac-ft/ mi^2/yr. Coast range watersheds (Table 9) may yield over 1 ac-ft/ mi^2/yr due to more erodible lithologies.

The sediments filling these reservoirs are not all coarse, but few data are available to describe the variations in size within the reservoirs. In general, gravels and sand are deposited in deltas prograding into the reservoirs from their upstream ends. However, sediment distributions are complicated by fluctuating water levels within the reservoirs. When reservoirs are drawn down, the influent channels incise through the delta deposits, and the locus of deposition shifts farther into the reservoir.

In Tables 8 and 9, sediment yields per unit area are presented for the reservoirs using the entire upstream drainage area and for only the area unregulated by upstream impoundments. The rationale for this practice is that upstream reservoirs trap sediment derived from their watersheds, so these areas should not be included in drainage area computations. This should be true for bedload, but not suspended load, especially given the potentially low trap efficiencies for smaller upstream impoundments.

Land-use practices in the watershed may increase sediment yields and thus sedimentation rates in the receiving reservoirs. Such changes may have already occurred since the 1940's, the last time some reservoirs were surveyed. Thus, projection of historic rates may not accurately indicate future sedimentation. Because of increased timber harvest in the watershed above Pardee Reservoir, the East Bay Municipal Utilities District (EBMUD) has initiated studies of cumulative watershed effects and development of sediment budgets for watershed lands so that potential impacts can be understood, and perhaps controlled before consequences have become severe.

The effects of fire in increasing sediment yield and reservoir sedimentation rates are well-documented in central and southern California. Los Padres Reservoir on the Carmel River experienced an average annual sedimentation rate of 19 ac-ft from 1947-1977, 22.5 ac-ft from 1978-1980. However, in the year 1977-1978, 555 ac-ft of sediment was deposited as a result of increased sediment yield resulting from the Marble-Cone Fire and heavy runoff over the following winter (Figure 5).

Hydrologic Alterations

Principal downstream gages on selected major drainages are listed in Table 10. In many cases, gages have been operating since the turn of the century; in others, since about 1940. Commonly, one finds that stream gaging did not begin until shortly before water development works were undertaken, so it may be difficult to compare river hydrology before and after the project. Moreover, the extreme interannual variability in streamflow in California means that the same hydrologic record could produce very different flow statistics if different periods were sampled. Accordingly, most of the pre-dam data compiled in Tables 11 and 12 were computed by the USACE using reservoir storage changes. Data sources are presented in Table 12.

The principal hydrologic modification effected by the large dams has been a reduction in flood peaks (Tables 11 and 12). Larger reservoirs such as New Exchequer and New Don Pedro are capable of swallowing even the 100-yr floods, with releases less than 10% of inflow. (The degree of modification depends on operations rules as well as capacity.) Smaller dams such as Camp Far West have little effect on the 100-yr flood peak. All these dams have reduced the magnitude of floods with return periods of

5 years and less.

These hydrologic modifications have potentially profound implications for channel form and sediment transport downstream. As discussed above, when the bankfull discharge, generally the 1.5-2.0 yr flow (Leopold et al. 1964), is reduced, the channels downstream may adjust by narrowing (Williams and Wolman 1984). Similarly, the decreased frequency of high flows results in a proportionally greater decrease in sediment transport. One effect of this is reduced frequency of mobilization of gravel beds, so that grains can become interlocked and difficult for spawning fish to move. A related impact is coarsening of bed material below dams resulting from winnowing of finer sediments without fresh supply from upstream, as discussed below.

Fine sediment delivered to the channel from tributary and other sources may accumulate because flows capable of moving it no longer occur. In many channels below dams, fine sediment has accumulated, impacting not only spawning gravels, but pool and cobble habitat as well (the details are described in a following section).

The effects of timing of tributary and mainstem peak are illustrated by Cottonwood Creek near Redding, which reached its peak discharge in 1986 while the Sacramento River was also high. Normally, the USBR would operate Shasta Dam to reduce flow in the mainstem Sacramento when high flows were expected from tributaries such as Cottonwood Creek. In the 1986 storm, however, the rainfall intensities telemetered from the Cottonwood Creek basin were so great that the USBR personnel assumed the instrument was malfunctioning and did not reduce flow in the mainstem. Thus the high flow in Cottonwood Creek joined the already high Sacramento River, causing a backwater effect in Cottonwood Creek and resulting in extensive deposition of gravel for 0.5 mile above the confluence (K. Buer, DWR, pers. comm. 1989).

Incision and Coarsening below Reservoirs

Examples of channel incision below dams in California are presented in Table 13. This listing is only partial because of time limitations, but would probably expand considerably if more extensive historical research could be undertaken. Documenting such channel changes requires searching out sequential bridge surveys in state and county files, retrieval of old gaging station records from Federal Storage in San Bruno, and other sources of data as described by Kondolf and Sale (1985). For the large number of rivers studied here and the range of impacts being addressed, compilation and analysis of these data were simply not possible. Nonetheless, the large body of literature documenting these effects in rivers outside California argues that such impacts would manifest in many California rivers.

The magnitude of incision below dams is related to bed material size and post-dam flood regime. Finer grained substrates show greater incision (Williams and Wolman 1984), while armor layer development in gravel bed rivers limits ultimate incision.

Incision below dams will proceed episodically, when reservoir releases or spills exceed the critical shear stress for the initiation of bed material movement. To the extent that reservoirs reduce the frequency of these high flows from pre-dam conditions, the rate and ultimate magnitude of incision will be limited. As the bed coarsens, the threshold of entrainment progressively increases. Moreover, incision directly below the dam results in a decrease in channel gradient. The effect of these two processes is to further reduce the progress of incision.

Counteracting these negative feedback processes is a tendency for the channel to narrow from vegetation encroachment. As the channel narrows, shear stress is locally increased by virtue of concentration of flow within a narrower cross section, resulting in greater depths for a given discharge.

The capacity and operation of reservoirs will determine the relative magnitude of incision and bed coarsening. A large reservoir that effectively swallows all flood flows will result in drastically reduced frequency of bed entrainment and thus limits the rate of incision downstream (e.g., Trinity Dam on the Trinity River, where Q_2 was reduced from 16,000 cfs to about 300 cfs by regulation)(Tables 11 and 12). Conversely, reservoirs with limited capacity and/or operations that do not include a flood control component (e.g. irrigation or municipal water supply reservoirs) will have relatively little effect on flood flows, so the bed will be mobilized at roughly pre-dam rates. As a result, incision will proceed rapidly, limited only by coarsening and gradient reduction (e.g., San Clemente Dam on the Carmel River, where post-dam Q_2 is within a few percent of pre-dam values in all but extremely dry years)(Matthews 1987).

An example of rapid incision occurred on the Yuba River below Englebright Dam during the 1986 flood. Englebright was constructed in 1940 as a debris dam to eliminate the continued flux of hydraulic mining debris downriver. The channel below the dam prior to 1986 was floored with large cobbles and boulders, apparently as a result of incision and coarsening following dam construction. USGS gage records indicate that the channel at the gaging station had been stable for many years, probably the result of the very coarse armor layer which protected the bed. However, the February 1986 flood was apparently large enough to mobilize even this boulder-scale bed material and cause up to 4 feet of incision as documented by sequential cross sections at the USGS gage (Figure 6).

Selected examples of bed-material coarsening below dams in California are presented in Table 14. This listing includes some entries based on anecdotal information. As noted above, quantitative data for pre-dam bed material size distributions are non-existent. In a number of cases, we have measured present bed material size below dams, and have relied on anecdotal information to estimate pre-dam conditions.

It is clear that bed material coarsening has occurred below many dams because reaches that were formerly heavily used by spawning salmon are now underlain by cobbles, boulders, or bedrock.

Fine Sediment Infiltration

Selected examples of fine sediment infiltration below dams in California are presented in Table 15. Again, few quantitative studies were found, and many of the entries are based on anecdotal reporting of changes observed by resource agency field personnel. Moreover, measurement of changes in fine sediment content in gravels is plagued with logistical and sampling difficulties (Lisle 1989). Thus, even if bed material samples had been obtained under pre- and post-dam conditions, unless the sampling scheme was carefully designed and implemented, the natural variability in bed material size would make all but the most extreme changes difficult to demonstrate with confidence.

Probably the best known and most dramatic example of fine sediment infiltration below dams in California is the Trinity River below Lewiston Dam, where abundant sand-sized sediment delivered from Grass Valley Creek accumulated in spawning gravels, rendering them unfit for spawning (Fredericksen, Kamine, and Associates 1980). Furthermore, sand has filled pools, reducing holding habitat for adults during migration, and also filled cobble areas, eliminating over-wintering habitat for juveniles and reducing aquatic invertebrate colonization, an important food source for the fisheries (A. Hamilton, USFWS, Lewiston, personal communication, 1991). As a result of these impacts, a wide range of studies is now underway to determine minimum flow releases required to enhance the remaining fishery below the dam. The Trinity River is an extreme case of flow modification, with 90% of the flow diverted from the basin into the Sacramento River, and the 2-year flow only 2% of its pre-dam value.

INSTREAM GRAVEL MINING EFFECTS

Instream gravel mining is widespread throughout California, although the type of operations is highly variable in part due to the nature of the available deposits and in part to the local regulatory framework. Major extraction sites are located close to the demand of rapidly growing urban areas, such as north and east of San Francisco Bay, the Sacramento area, the Stockton area and other growing Central Valley cities, and Southern California. In some locations, virtually all instream mining has been replaced by floodplain pit mining (such as along the Tuolumne River), not necessarily for environmental reasons, but rather that instream gravels were so limited below La Grange Dam due to the lack of recruitment and because demand had increased so rapidly that much larger sources of material were needed. In other areas, such as Stony Creek and Thomes Creek, which are dry for long periods each year, almost all of the extraction remains instream.

Channel Incision

Table 16 presents data on channel incision attributable to instream gravel mining from files of Caltrans (California Department of Transportation), Division of Structures, Sacramento and other sources. Many of these examples of incision were documented from sequential bridge surveys or soundings and have been attributed by Caltrans staff to nearby instream gravel mining, although comprehensive studies may not have been conducted. Photographs included in bridge files show active gravel extraction immediately upstream or downstream of many of the bridges. The temporal and spatial patterns of the incision indicate that instream gravel extraction is responsible. In many cases, local hydraulic adjustments to the presence of the bridge occurred within a few years of construction, after which the bed was stable until commencement of instream mining, when incision abruptly began.

In certain cases, excellent documentation exists to pinpoint causes of incision. On Stony Creek in Glenn County, Swanson and Kondolf (1991) conducted a detailed study of historical channel changes and changes in sediment flux, using sequential aerial photographs, historical channel surveys, analysis of reservoir sedimentation rates and permitted extraction rates. Incision resulting from construction of Black Butte Reservoir (in 1963) extended downstream less than 8 miles. A distinct episode of incision (up to 16 ft from 1973 to 1990) centered at the Highway 32 bridge crossing 13 miles below the dam was clearly related to intensive instream gravel extraction in pits immediately upstream and downstream (Swanson and Kondolf 1991).

Perhaps the best known examples of channel incision resulting from instream gravel extraction are found on the Russian River below Healdsburg and on Cache Creek in Yolo County. On the Russian River, extensive wet pit mining in the active channel in the 1950's and 1960's effectively lowered the bed in excess of 10 ft over seven river miles, with a maximum incision of 18 ft. As a result, the form of the river has been changed from a wide, braided channel to a deeply incised channel with a straighter course. By the mid-1960's, channel pit mining was abandoned and replaced by bar-skimming and terrace mining (Collins and Dunne 1990). Cache Creek was the source for 80-90 million tons of aggregate from 1905 to 1983. As a result of this massive extraction, channel incision of up to 27 ft has occurred, as documented by stage discharge relations at a USGS gaging station, and repeat surveys of longitudinal profiles and bridge cross sections (Woodward-Clyde Consultants 1976). The future management of this reach remains highly controversial, and was subject of a recent EIR and protracted public hearings (Dames and Moore 1991). The incision of Cache Creek has resulted in a loss of alluvial groundwater storage potential, although overdraft complicates the groundwater picture (Environ 1980).

Undermining of Highway Bridges

One of the consequences of channel incision is undermining of structures, such as pipelines, canal crossings, and highway bridges. Table 17 presents a partial inventory of bridge repair costs for state highway bridges through 1984 that have been attributed to instream extraction. This table is only a partial listing, and with further research the figure for costs through 1984 would likely double (R. Hackett, Caltrans Division of Structures, unpublished memo 1984).

Intensive extraction on the Santa Clara River in Ventura County resulted in failure of the Highway 118 bridge during the 1969 flood, resulting in repairs costing $730,000 (in 1969 dollars). The Highway 67 bridge over the San Diego River was completely replaced in 1981 (at a cost of $3.3 million) as a result of extraction-related undermining. Incision on Stony Creek, discussed above, will require bridge repairs costing $1 million (Table 17).

Bed Coarsening

Instream mining has selectively removed spawning sized gravels from many rivers, although documentation is poor. One of the best documented examples is the Upper Sacramento River, in which the impacts of upstream dam construction were compounded by intensive in-channel extraction (for construction of the dam) and subsequent intensive extraction from tributaries (Parfitt and Buer 1980). Construction of Shasta Dam (completed in 1944) required 7.1 million yd^3 of aggregate, which was derived from two large gravel bars in the Sacramento River downstream of the dam site. The entirety of one bar was excavated, locally to a depth of 50 ft (Parfitt and Buer 1980). THe gravel remaining in the channel after this massive removal was subsequently transported downstream by clearwater releases from the dam, leaving only a lag of cobbles, boulders, and bedrock in the reach near Redding.

With continued urbanization of the northern Sacramento Valley, extensive gravel extraction occurred in tributary channels. On Clear Creek, the combination of intensive mining and subsequent flood flows has resulted in a channel scoured to bedrock in many places and armored with coarse material elsewhere (Parfitt and Buer 1980). Bed coarsening on these tributaries has directly reduced potential spawning grounds in the tributaries themselves and greatly reduced the remaining gravel supply to the mainstem Sacramento River below Shasta Dam. These tributary effects have contributed to coarsening on the mainstem.

An example at a smaller scale is San Simeon Creek in San Luis Obispo County, where bar skimming over a 30 year period has resulted in development of a coarse cobble lag and incision to hardpan over a reach of about 0.5 mi upstream of the extraction (Table 14).

Although in this study we could locate documentation for relatively few examples of bed coarsening resulting from instream mining, we expect that this effect must be manifest in other channels.

Channel Instability

Channel instability resulting from instream gravel mining could be expected, given the disruption of pre-existing channel geometry (Collins and Dunne 1990). Stony Creek at the Highway 32 Bridge illustrates this phenomenon, as the incised channel has migrated laterally towards bridge abutments (Swanson and Kondolf 1991).

EXISTING POLICIES: RESERVOIRS

Dam Safety

As noted above, dams higher than 25 ft or with capacities exceeding 50 ac-ft come under the jurisdiction of DSD, unless the height is less than 6 ft or capacity is less than 15 ac-ft (Figure 7) (DWR 1988). DSD is required to inspect these dams at least annually for evidence of safety problems.

DSD (1991) requires that low level outlets be operable so that reservoirs can be drawn down in emergencies. For new dams less than 5000 ac-ft, outlets must be designed to drain 50% of the reservoir volume in 7 days. This rule cannot be applied to larger reservoirs because of the unrealistically large outlet pipes that would be required, so the criteria require the dam to be "well engineered." For example, the requirement at New Spicer Meadow Dam is that the reservoir level can be dropped to 10% below the fixed spillway. At Oroville Dam, two 5-ft diameter valves near the base of the dam were used during reservoir filling but rarely since. Even with 5-ft outlets, draining such a large reservoir could not possibly be accomplished in anything like 7 days (D. Babbitt, DSD, personal communication 1991).

For smaller reservoirs, DSD requires owners to exercise their valves on a periodic basis to demonstrate operability and to remove accumulated sediments that could interfere with operability (D. Babbitt, DSD, personal communication 1991). The downstream impacts of sluicing can be significant, and they are discussed in more detail below.

As noted above, reservoirs that have completely filled with sediment pass out of the jurisdiction of DSD because their capacities are less than 15 ac-ft (Figure 7).

Sluicing

Sluicing is conducted in small reservoirs and diversion structures to remove sediments accumulated above the dam as well as for maintenance of outlet works. Intentional sluicing is typically accomplished by opening the outlet pipe or sluice gates and permitting the reservoir to draw down sufficiently to resuspend sediment. Accidental sluices have also occurred during maintenance or repair work. Recently, these episodes have come to the attention of regulatory agencies and resulted in substantial cleanup costs for the dam operators.

CDFG has long been concerned about the impacts of sluicing because it is frequently conducted during summer months, when flows are inadequate to disperse sluiced sediment (J. Mensch, CDFG, personal communication 1991). On dams larger than small diversion structures, the sediment accumulated around outlet is usually silt and clay. Release of this material and its deposition downstream can be extremely deleterious to aquatic life. For example, opening of the low level outlet on Los Padres Dam on the Carmel River in 1980 resulted in a large fish kill (Buel 1980); the dam operator has since been required to use a suction dredge to maintain the outlet (D. Dettman, MPWMD, personal communication 1990). Sluicing of smaller diversion dams can release sand to downstream reaches, as occurred in the South Fork Feather River below Forbeston Reservoir in 1986, when a layer of sand (about 5-10 mm thick) was deposited over the entire channel width for an undetermined distance downstream (Kondolf 1986).

Two recent, controversial sluicing incidents, described below, illustrate the serious nature of the problem.

Our House Reservoir (capacity 285 ac-ft) on the Middle Yuba River, completely filled with sediment during the February 1986 stormflow because of the high influx of sediment and because the sluice gates were inoperable. During the following August, the dam operator, Yuba County Water Agency (YCWA) began mechanical removal of the accumulated sediment, which was trucked out of the canyon to a disposal site. During this work, the cofferdam directing the river flow around the work area failed. The sluice gate was open, and sediment began to flush from the reservoir through the gate, spreading out over the channel bed downstream. The gate was not closed and the situation was not rectified for three days, during which time a plume of turbid water reached the Highway 49 bridge crossing 8 miles downstream. Bathers at the bridge complained to the CDFG warden, who visited the dam and ordered the sluice gate closed immediately. By this time, an estimated 15,000 yd^3 of sand and gravel had deposited over a 4000 ft reach below the dam (EBASCO Environmental 1989).

In subsequent negotiations with resource and regulatory agencies, YCWA (and PG&E, with whom YCWA contracted operations) agreed to mechanically remove 8000 yd^3. This operation required construction of a road into the channel, operation of heavy equipment in the channel bed, and rearrangement of boulders in the bed to permit excavation to proceed. Total cost of this operation was $1.3 million, excluding costs of study design and subsequent monitoring. Much of the remaining sediment (estimated at 7000 yd^3) was transported downstream by spills in 1987-1989, as shown in Figure 8. Spills during 1987 and 1988 (Figure 9) were relatively small and brief; their net effect was to cause the tongue of sand to extend downstream in steps several hundred ft long, progressively filling pools. The larger spill of March 1989, however, effectively suspended sand, scoured pools, and dispersed sand in harmless concentrations over three miles downstream. The cycle of deposition and scour is illustrated in Figure 10, sequential surveys of Cross Section 5d across a pool (Figure 8). This pool, unaffected by the initial sluice, was buried by the prograding tongue of sediment during the November 1988 spill, and the partially scoured by the March 1989 spill (EBASCO Environmental 1989).

The progressive extension of sediment tongue during the modest spills of 1987 and 1988 contrasts with the dispersion of sediment in the large 1989 spill, and emphasizes that when sediment is introduced at low flows, mitigation is difficult. However, at high flows, sediment is readily dispersed, in a fashion similar to the natural movement of sediment through the river system.

A similar event occurred below Poe Dam on the North Fork of the Feather River in 1988. During maintenance work on a spillway gate, approximately 23,000 yd^3 of fine sands (and an undetermined volume of silt) were accidentally released. The sand deposited in three pools below the dam. The dam operator, PG&E, agreed to mechanically remove sediment from the first pool and make a controlled release of 2500 cfs for two days to flush the remaining sediment through the system. During extraction of the sediment from the first pool, an unusually large storm hit the Feather River basin and a large spill (peak flow of approximately 18,000 cfs) occurred. On the recession limb, PG&E maintained a discharge at the required 2500 cfs to complete the two-day period. Subsequent monitoring of cross sections and streambed materials indicated that the sluiced sediments had been completely flushed from the system (Ramey and Beck 1990).

It is notable that in the absence of the fortuitous storm and spill, the required 2500 cfs release would have been quite expensive in terms of lost hydroelectric revenues. The costs of mechanical removal, monitoring study, and 2500 cfs release for 24 hours were not reported (Ramey and Beck 1990).

Also on the North Fork of the Feather, Rock Creek Reservoir (capacity 4660 ac-ft) has filled with sediment to the point normal operation is compromised. CDFG has determined that no sluicing will be permitted, so the dam operator, PG&E, is considering alternative methods of sediment removal. The most promising removal method is a slurry pipeline to a distant disposal site (T. Lambert, PG&E, personal communication 1990). Removal and disposal of sediment from this reservoir is expected to cost in excess of $20 million (E. Stassevich, PG&E Hydrogeneration, personal communication 1989).

Curiously, PG&E's only established guidance to personnel for sluicing reservoirs is contained in a bulletin issued in 1967 and revised in 1970 (PG&E 1970). This bulletin gives limited guidance to field personnel. Subsequent discussions with PG&E personnel and others familiar with the operations indicate that the sluicing efforts lack a coherent policy updated to account for current environmental concerns and regulations. In general, decisions regarding when to open sluice gates are made by field personnel on the spot, and evidently based on subjective judgement. Not only do these personnel operate without established guidelines, but they are not required to document periods in which gates were opened and closed (W. Pahlen, PG&E, personal communication 1989).

Sluicing would be far less damaging, and in some cases beneficial, if done only during high flows, especially if gates were closed before flow recession. At high flow, the sluiced sediments would be transported and dispersed downstream, mimicking the natural movement of sediment through the system prior to construction of the dam and interruption of the sediment flux.

Development of a coherent policy would involve quantification of accumulated sediment, specification of flow thresholds for opening of sluice gates, and specification of duration of sluicing, which should be tied to duration of high flow. The rules for sluice gate operation should be specified in detail so that resource agencies can agree to them beforehand, permitting the dam operator to respond promptly to rapidly rising flood flows.

The present lack of a coherent sluicing policy may result in enormous expense to rate-payers for sediment removal and potentially significant environmental impacts when sluicing is conducted at low flows. The costs of developing scientifically-based policies and protocols for sluicing would be minor compared to the potential costs of sediment removal from a single reservoir.

Flushing Flows

Flushing flows are releases from dam designed to remove fine sediment from downstream spawning gravels and other aquatic habitat components (Kondolf et al. 1987). These periodic high-flow releases may also be designed for maintenance of the channel cross section and riparian vegetation dynamics. A range of methods has been employed to establish flushing flow releases in various channels (Reiser et al. 1988), but the need for data collection as part of standardized methodology is not always appreciated.

There is a fundamental dilemma regarding flushing flows that apparently is not widely appreciated. Simply stated, the flows required to clean gravels are not very different from the flows that will transport gravels downstream altogether. From existing knowledge of sediment transport, it is probably not possible to specify a flow that will clean gravels to a depth greater than one framework grain diameter without transporting at least some of the gravels themselves. Because the reaches of interest lie downstream of dams, upstream recruitment has been eliminated, and transport of remaining gravels from the reach constitutes a net loss.

A program of flushing flows must be coordinated with a program of gravel enhancement (discussed below) to mitigate for the effects of gravel transport from the reach. Recommendations for specifying flushing flows constitute a separate area of study and are beyond the scope of this report.

EXISTING POLICIES: GRAVEL MINING

At present, instream gravel mining is largely unregulated because many operations are grandfathered (under "vested rights"), the relevant state legislation is weak, and information on extraction volumes has generally been unavailable.

Regulation of Instream Mining

The principal statewide regulation of instream gravel mining is conducted under SMARA, the Surface Mine and Reclamation Act of 1975 (with subsequent amendments). SMARA places most responsibility for regulation on lead agencies, usually counties and cities. Lead agencies must receive approval from the State Mining and Geology Board for a "mining ordinance". Under SMARA, all extractors are required to submit "reclamation plan", describing the existing environment and the intended ultimate reclamation of the site. The lead agencies are responsible for accepting reclamation plans. The California Division of Mines and Geology (CDMG) will provide technical assistance in reviewing reclamation plans, but CDMG acts in an advisory capacity only.

Operations begun after January 1, 1976 are required to obtain a county use permit, but older operations are "vested" and do not require a use permit unless they propose to expand their boundaries.

Instream gravel mines also require a CDFG 1603 Streambed Alteration Agreement, issued by the CDFG warden. Conditions under the 1603 permit are often more stringent that those under the use permit, especially in northern Californian rivers with anadromous salmonid populations. CDFG has limited power to refuse to issue a 1603 agreement, and in any case, CDFG appears not to have had the political clout to stop instream mines in important salmonid habitats.

In most cases, instream mines have not obtained USACE 404 wetland permits, because the permits are regarded as necessary only if the project involves filling (and gravel mining is excavating). However, this is being reevaluated by USACE personnel because gravel extraction operations generally involve grading, which by definition involves some fill (L. Varnahagen, USACE, personal communication 1991).

Shortcomings of Existing Regulation

SMARA is primarily oriented to surface mines and their reclamation, based on the model of the open-pit or strip mine. If such mines are abandoned, they may constitute unsightly and dangerous scars on the land, so the state seeks to insure that the mine operator will reclaim the mined land to productive use. The concept is reasonable when applied to essentially static environments that can be disturbed within a confined area, without affecting surrounding areas, and then reclaimed. The extensive surface mine south of Teichert Construction Company's Perkins Plant in Sacramento is an example. After being mined, the land is returned to productive agricultural use, only shifted down by about 12 ft.

Under SMARA, the reclamation concept has been applied to extraction of gravel from active riverbeds as well, despite very different conditions. The beds of rivers and streams are extremely dynamic environments. As discussed above, disturbance of the bed in one locality can result in propagation of the impact for long distances up- or downstream. Thus, it is not possible to disturb one site in isolation from the environment and "reclaim" it. The reclamation concept cannot be intelligently applied to an active riverbed.

Under SMARA, lead agencies are responsible for reviewing reclamation plans, as well as conducting CEQA review. Unfortunately, counties and cities can generally not afford the technical staff needed to evaluate reclamation plans or to monitor performance of the extractor. Moreover, counties - especially small rural counties - may be subject to political pressure from extractors. Because CDMG has only an advisory role under SMARA, the law lacks effective enforcement.

Moreover, production figures have been consider proprietary information, and this information has not been available to the public or other agencies. Recent (1991) amendments to SMARA include reporting requirements, which should make rationale planning and management more possible.

Many reclamation plans are weak, containing little evidence that the authors made a serious effort to understand the environmental impacts of the operation and most effective means of restoring those values. The SMARA guidelines for the reclamation plan section "Environmental Setting" follow, with that section excerpted in its entirety from one reclamation plan that was accepted by Glenn County.

SMARA Guidelines for Environmental Setting:

> Describe the project site as it exists before the project, including information on topography, soil stability, plants and animals, and any cultural historical or scenic aspects. Describe any existing structures on the site, and the use of the structures. Attach photographs of the site. Snapshots or polaroid photos will be accepted.

Applicant section on Environmental Setting:

> The present site is basically a level area of sand and gravel covered with bamboo, grasses and some trees. Area contains usual creek side wildlife. Does not appear to be any cultural, historical or scenic aspects. Existing buildings are old out buildings of an insignificant nature.

Source: Swanson and Kondolf 1991, Appendix F

Survey of County Lead Agencies

In order to assess the effectiveness of impact evaluation and monitoring among lead agencies, two graduate students at UC Berkeley (Sue Huse and Tom Murphy) conducted a telephone survey of 56 county lead agencies. Of these lead agencies, only 9 have established limits for mining that are tied to hydrology or channel conditions, only 11 required stream channel cross sections and some aerial photography as part of the monitoring requirement. Only 5 of the lead agencies had taken a regional look at gravel resource management and implemented studies of sand/gravel replenishment; another 3 were studying such a regional approach. Most counties had no data on actual extraction volumes, no data on amounts mined instream vs off-channel, and no systematic monitoring program.

Thus, existing lead agencies under SMARA appear poorly equipped to deal with the responsibility thrust upon them by SMARA.

Role of Caltrans

Because of the serious impacts upon highway bridges, Caltrans pushed for an amendment to SMARA in 1984 requiring all applicants for new instream mining permits to notify Caltrans if the proposed mine would be within 1 mile of a Caltrans bridge. However, Caltrans is limited to a review capacity, and can only comment upon the proposal.

Caltrans has initiated a statewide inventory of bridges with potential scour problems. Of the 15,000 bridges over water in California, about 150, or 1%, are considered to critically threatened by scour (C. Crossett, Caltrans, personal communication 1990). The agency has begun efforts to identify the cause of these problems and to develop approaches to prevent such problems in the future.

RECENT RESTORATION EFFORTS

Recent restoration efforts have included importing gravel into gravel-deficient channels, scarification of immobile gravel beds, construction of artificial side channels with conditions suitable for spawning fish, flushing flows, construction of sediment traps, mechanical excavation of pools filled with sediment, and restoration of natural channel geometry and riparian vegetation in disturbed streams. Flushing flows were briefly addressed in the previous section and will not be considered further.

Gravel replenishment projects

Table 18 presents a partial listing of gravel replenishment projects in California compiled in the course of this study. As with many of the restoration activities described in this section, the implementation of these gravel replenishment projects has begun very recently: 13 of the 16 projects listed in Table 18 have been completed since 1987, with 8 in 1990 or 1991. The costs and scale of the projects run from placement of 40 yd^3 in the Carmel River in 1990 at a cost of $580 up to anticipated placement of 8,000 yd^3 in the Sacramento River below Shasta Dam at a cost of $19 million over the next decade. Costs per cubic yard are highly variable depending on access limitations and other site work required. Many projects fall in the \$15-30/yd^3 range with economies of scale evident for some of the larger projects. For smaller projects with difficult access or long transport distances, costs of up to \$200/yd^3 were reported.

Expensive as the Sacramento River efforts are, it is unlikely that they can bring about a long term solution. Any gravels placed in the main channel are likely to be scoured and progressively moved downstream by floods (e.g. the 1979 project on the Sacramento River, see Table 18). Thus, the very nature of the problem (progressive bed coarsening during clearwater spills) precludes a one-time solution. Gravel replenishment must be undertaken on a periodic basis, with the frequency of placement depending upon the magnitude and duration of reservoir spills capable of entraining the gravels.

Methods of gravel placement range from hand placement by volunteers or the California Conservation Corps to sluice pipes for sites with access difficulties to dumping by trucks in piles that will be reworked and spread naturally downstream by subsequent flows to placement by helicopter for particularly remote or inaccessible sites.

Spawning gravel replenishment is perhaps most effective when combined with construction of limited in-channel structures to retain as much gravel as possible on-site. These structures have been constructed along many rivers (e.g. Klamath, Trinity, Sacramento, Tuolumne) and may consist of large boulders, gabion sills, or log sills.

Unfortunately, an important component of restoration projects, post-construction monitoring, appears to be haphazard: there are few examples of systematic post-project evaluation of these efforts. Moreover, the agencies undertaking these efforts often know little of similar efforts elsewhere. When interviewed after completing a gravel replenishment project in Lagunitas Creek, MMWD director Leo Cronin was quoted in the Point Reyes Light as stating, "This is experimental. I've never seen anything like this." Efforts to restore gravel supplies to stream can only benefit from the experience of other such projects, especially if their success were systematically evaluated.

Artificial Spawning Channels

The construction of artificial spawning channels, on the other hand, has been practiced for many years to compensate for blocked or inundated spawning areas. This mitigation technique has probably been more common because it is similar in some respects to a hatchery and would thus have a more traditional appeal, and being isolated from the active channel, typically only requires significant maintenance following large floods, if facilities exist to filter out or otherwise block fine sediments from infiltrating the gravels. Table 19 presents selected examples of artificial spawning channel construction. The type of artificial spawning channel constructed may range from concrete-lined to the usage of natural side channels requiring only the construction of local hydraulic controls and stocking with spawning gravels. Spawning channels have also been constructed across large point bars (e.g. along the Trinity River). The success of these facilities has varied substantially: the Merced River spawning channel increased salmon stocks dramatically between 1966 and 1973 (Hazel et al. 1976, p. 510), while the Tehama-Colusa Fish Facilities have experienced numerous problems including insufficient water supply, excessive water temperatures, adverse hydraulic conditions, growth of aquatic weeds, and disease (USRFRHAC, 1989).

With proper design, construction, and maintenance, artificial spawning channels can be an effective means of mitigation.

Riffle Scarification

This restoration technique involves cleaning of compacted gravels that have been infiltrated by fine sediment. The most common method has typically been "riffle ripping", where a bulldozer with ripping attachments scarifies known or potential spawning sites. The technique is simple and relatively inexpensive, but must be repeated periodically and causes short-term increases in turbidity. Bulldozer ripping has been conducted on the Trinity and Sacramento Rivers, and along Clear Creek. Alternatives to ripping with heavy equipment have been explored on the Trinity River, with the most promising involving use of suction dredges. This application has the advantage of removing all fine sediment directly from the channel, and that is may be used in deeper water. Unfortunately, it is considerably more labor intensive and expensive.

Pool Excavation

Downstream of dams where mainstem hydrologic alteration in combination with high sediment yields from tributaries leads to the accumulation of sediments in pools, restoration has taken the form of pool excavation through dredging. Furthermore, fine sediment may reduce pool volume and depth even in unregulated streams if land use changes upstream, such as logging, result in sediment delivery in excess of transporting capacity. Anecdotal information from residents and fishermen along both the Russian and Garcia River indicates this scenario has occurred (C. Bell, professional fishing guide, personal communication, 1991).

On the Trinity River, where tributary sedimentation is particularly severe, the USFWS restoration program dredged 3 pools in 1990 using hydraulic excavators and draglines. Additional pools are planned to be excavated in 1992 using a suction dredge (A. Hamilton, USFWS, Lewiston, personal communication, 1991). Without a reduction in sediment supply, however, the pools will likely refill quickly, providing only a short-term improvement in habitat values.

On the Garcia River in 1990, a gravel operator was requested to excavate "pools" by the local CDFG biologist to compensate for loss of habitat values from previous bar skimming operations. The material extracted was stockpiled by the operator for future processing and sale. Unsupervised work resulted in the excavation of large trenches that bear little resemblance to natural pools. Detailed surveys by CDFG and the Mendocino County Water Agency following the excavation will enable the tracking of potential knickpoint migration and other impacts (G. Heise, CDFG Hydraulic Engineer, personal communication, 1991).

A gravel operator on the Russian River has proposed similar excavations, arguing that substantial habitat would be created. Unfortunately, the desire on the part of an operator to extract as much material as possible, creating unnaturally large deviations from the equilibrium profile, would have the potential to cause significant impacts, and can hardly be considered habitat restoration. While pool excavation has a legitimate place in stream and habitat restoration projects, as discussed below, the appropriate scale is too small to provide for the needs of gravel operations, and, furthermore, all of the coarse sediment (gravels and larger) should be returned to the channel.

Construction of Sediment Traps

This type of restoration technique has been primarily limited to tributaries which are delivering high sediment loads (e.g. Grass Valley Creek on the Trinity River), although Gardiner (1988) describes the installation of a sediment trap in the mainstem of a river to reduce sand transport downstream into a restored reach. These sediment traps may range from large debris basins (numerous examples in southern California) to pools with high trap efficiencies (Grass Valley Creek just above the confluence with the Trinity River). In general, though, such structures will require frequent maintenance in order to maintain capacity.

Stream Restoration

Streams and rivers may have become degraded from a wide variety of human impacts, and the nature of the disturbance also comes in many forms. Impacts typically center around channel instability, either of the profile or planform characteristics, leading to erosion and downstream sedimentation, loss of riparian vegetation, and loss of habitat values. In recent years, as increased awareness has been focussed on these problems, the development of a stream restoration movement has occurred. Due to the scale difficulties of working on the larger rivers, however, more attention has been placed on smaller streams. Stream restoration is comprised of "biotechnical" techniques that seek to reestablish the natural characteristics of the site prior to instability or loss of habitat value, by a combination of structures and vegetative plantings. Many of the techniques described in previous sections are included in restoration programs, although the emphasis lies on the entire system, not just streambed materials.

For example, on the Carmel River, restoration of disturbed areas has involved reconstruction of channel geometry to approximate historically "stable" conditions, replanting of riparian species along the "restored" banks and floodplain, re-creation of a pool and riffle sequence connected by a clearly defined low-flow channel, and replacement of streambed gravels after mechanical sorting (Matthews 1990). Enhancement of spawning gravels is one component of a systems approach to habitat restoration.

12. ALTERNATIVE STRATEGIES FOR COARSE SEDIMENT MANAGEMENT

Objectives of Coarse Sediment Management

The management of coarse sediment must recognize the interactions among sediment sources, transport pathways, and sinks, so that proposed actions are considered not in isolation, but rather as part of a system-wide (i.e. watershed) approach.

Goals of a coherent, comprehensive program of coarse sediment management should include:

1. establishment of a balance between the Public Trust obligations for maintenance and enhancement of aquatic and riparian habitat and other beneficial uses for water

development and instream mining

2. development of standard protocols, methods, and techniques for reservoir operations (such as operating rules and sluicing), mitigations (such as flushing flows, gravel enhancement, side channel construction), and monitoring and the active dissemination of these techniques to those in regulatory or management capacities

3. protection of public and private facilities from the impacts of instream mining

4. restoration of existing degraded rivers in order to assist in carrying out the mandate of SB 2261 requiring significant improvements in fishery resources by the end of this century

5. integration of coarse sediment management into the larger framework of watershed planning and management

General Management Recommendations

The development and implementation of comprehensive river basin management plans is essential in an era of competition for limited resources, and such watershed plans must consider sediment issues. Sediment supply must be addressed on a watershed-scale, while aggregate demand must be viewed on a regional scale, which may encompass several watersheds. This process should be funded by user fees paid by those who derive benefit from water developments and harvesting of aggregate, such as hydroelectric power producers and users, irrigation districts, water supply districts, flood control districts, and aggregate producers and users.

State-level and statewide regulation and enforcement of standards is essential. Comprehensive river basin management plans are needed to balance beneficial uses with natural resource protection and restoration. The planning we envision would be unlike traditional river basin development, in which hydroelectric generation, irrigation diversions, flood control, and gravel extraction have been pursued at the expense of natural resources. Instead, the existing uses must be reviewed in light of impacts upon the environment, and all new projects must incorporate a significant element of habitat restoration, as done now in the United Kingdom under the auspices of the National rivers Authority (Gardiner 1988, 1990).

Specific Management Recommendations

One approach to managing coarse sediment throughout river systems involves the recognition of geomorphically distinct environments based on the availability of sediment, and the integration of this knowledge of sediment supply with the location in a given watershed of reservoirs. Thus, our recommendations for management strategies differ for three sediment supply categories (aggradational, equilibrium, or degradational) and three distinct settings: reaches below reservoirs, reaches without reservoirs upstream, and reaches above reservoirs. Aggradational environments are limited in most of California, the exceptions being primarily in more arid regions of California (predominantly southern) where alluvial fans are an important feature. Other locations are limited to severely disturbed watersheds (generally by logging), or to areas impacted by unusually large floods which deliver large volumes of sediment to channels through landslides and debris flows.

Reaches Downstream of Reservoirs

These reaches are the most sensitive to manipulate of coarse sediment because all coarse sediment yield from the upstream basin is trapped by the reservoir. Instream gravel mining should be prohibited in all such reaches. If terrace deposits are present, these may be exploited provided sufficient setback from the active channel to allow for the development of a riparian corridor where lacking or the expansion of an existing but areally limited corridor. This riparian corridor will substantially reduce the risk of channel avulsion, while providing wildlife habitat. The pits should be designed to maximize wildlife habitat upon reclamation. As mitigation for the impacts of dam construction and terrace extraction, operators should be required to enhance existing instream habitat through gravel replenishment and stream restoration projects, such as that underway on the Tuolumne River (Chuck Falkenstein, M.J. Ruddy & Sons, personal communication 1991). The amount and frequency of gravel replenishment may be calculated based upon the channel hydraulics and post-dam flow regime. Monitoring should be incorporated into these projects, so that with experience the most effective techniques can be developed.

Dam operators should be required to make more effective flushing flows which mimic the natural pattern of streamflows (magnitude, duration, and seasonal distribution) to the greatest extent feasible. Such releases are necessary to flush fine sediment from gravels, particularly after storms which would cause fine sediment to be delivered from downstream tributaries to the mainstem. The magnitude of flushing flows may be estimated from measurement of bed material size distribution, velocity profiles, and channel geometry, while the duration of the flow can be estimated from the volume of fine sediment to be flushed and the size of the dispersal area.

Tributary management becomes essential in highly regulated systems to reduce mainstem sedimentation, and the need for frequent flushing flows. Tributary watershed management involves monitoring of flow and sediment delivery, changes in land use, and implementation of Best Management Practices (BMP's) for operations such as timber harvest or road construction. In severe cases, such as the Trinity River, debris dams or other sediment traps may need to be constructed, funded by those impacting the watershed. Maintenance of the traps should involve screening and removal of fine sediment, while allowing gravels to continue moving downstream.

Reaches Upstream of Reservoirs

Much of the watershed area upstream of reservoirs is relatively inaccessible, typically only has minor alluvial deposits, and is farther from aggregate demand, thus has little pressure for extraction. Upper watershed areas are typically managed for resident trout populations, if downstream dams block anadromous fisheries migration. The primary management aspect needed in these areas is watershed management to reduce sediment yields which ultimately result in the loss of reservoir capacity.

Reservoir Management

The interface between river and reservoir at the upstream end of the reservoir pool provides a unique opportunity to obtain aggregate with virtually no environmental impacts and at the same time improve reservoir capacity. Coarse sediment is deposited in a delta that progrades into the reservoir depending on pool elevation. Extraction of coarse sediment from reservoir deltas should be undertaken where access is feasible. This is particularly important at smaller, run-of-the-river type diversion structures. Extraction has all of the advantages of instream mining (replenishable, well-sorted, clean, extract with standard heavy equipment) without any of the drawbacks (environmental damage, land acquisition costs, reclamation costs) except haul distance, although many of the foothill reservoirs would be within a reasonable haul distance. This strategy has been used at Lake Combie (capacity 5500 ac-ft) on the Bear River and is used extensively in Europe (Hack 1986). Furthermore, it would be a relatively simple matter to take a portion of the gravels extracted from the delta and inject them downstream of the dam as gravel replenishment. In most reservoirs, seasonal drawdown of the pool would provide a predictable extraction season, that would be even longer during droughts as opposed to instream mining which may see no replenishment to the site for several years during extended drought periods.

A management strategy recently developed in Europe to reduce sedimentation problems for run-of-the-river structures involves the construction of training walls within the reservoir pool to maintain a narrower channel (Hack 1986). A narrower channel will more easily resuspend fine sediment deposits allowing more complete flushing during floods or sluicing events, reducing maintenance costs.

Reaches without Reservoirs

Unless obvious stream bed aggradation is occurring, it must be assumed that sediment supply is in approximate equilibrium with transport capacity. Instream mining should be prohibited except in cases of fine-grained ephemeral channels that are not used by anadromous fisheries even on a seasonal basis. If instream mining is allowed, locations should be utilized that reduce risk to public and private facilities, such as bridges, a maximum excavation depth should be set to minimize risk of knickpoint migration, and extraction should be performed by a modified bar skimming method that maintains low-flow channel confinement to reduce the risk of instability. Similar considerations for terrace or flood plain mining as previously described should be used.

Alternative Sources of Gravel

An inventory of gravel sources as an alternative to instream mining has been developed. The sources are ranked in order of preference from a perspective of minimizing natural resource impacts.

1. Dredger tailings: extensive areas of dredger tailings, remnants of hydraulic mining in the mid to late 1800's, are present on the flood plain along many central Sierran rivers, including the Mokelumne, American, Bear, Yuba, and Feather Rivers. These tailings fill flood plains, increasing flood risk, reduce areas of riparian habitat, and are unsightly. Utilization would clean-up floodplains allowing riparian restoration, as the Teichert operation on Mississippi Bar, Lake Nimbus demonstrates.

2. Reservoir deltas: as described above, extraction from deltas has many advantages, limited only by the feasibility of access and hauling distance.

3. Quarries: there are a number of locations with extensive deposits of Tertiary or Pleistocene gravels away from the modern stream channel that would have many fewer impacts than instream mining. Hardrock quarries are options in some locations depending upon lithology, and intended use.

4. Terrace mining geomorphically isolated from active channel (dry pit): this type has no risk of flood-caused failures, and is easily reclaimed to agriculture or housing following completion of extraction. An example is the Teichert operations in southeast Sacramento.

5. Terrace mining not geomorphically isolated from active channel (dry pit): if extraction does not proceed below the water table, reclamation is straight-forward, and there is considerably less disaster potential when protecting levee fails. Maintain minimum 200 foot setback for riparian corridor and buffer.

6. Terrace mining not isolated (wet pit): this type has limited reclamation possibilities, and has greater damage potential from levee failure.

7. Instream mining: controlled extraction through modified

bar skimming, limited to areas with minimal habitat.

CONCLUSIONS

The problems created by human manipulation of coarse sediment resources are generally treated at a site-specific basis, however, the effects are pervasive and profound with substantial costs and severe environmental impacts. The failure to effectively mitigate for the loss of spawning gravels due to dam construction and instream gravel mining is partially responsible for the drastic declines in anadromous fisheries resources in California in the last 50 years. The need for a revised approach to coarse sediment management that incorporates watershed- and regional-scale planning is evident. Alternative management strategies have been applied on a piecemeal basis, and lack of careful, comprehensive monitoring has prevented a thorough evaluation that would lead to the development of standard procedures and techniques. Furthermore, the regulatory framework is clearly inadequate to assess the potential impacts of proposed operations and to manage and monitor existing operations. The costs to those who benefit from, or create the demand for, water development and/or instream gravel mining do not include the actual environmental costs of these activities.

Recent trends in legislation regulating instream mining and in the implementation of small-scale restoration or enhancement projects provide the basis for hope that the situation is improving.

REFERENCES CITED

USRFRHAC (Upper Sacramento River Fisheries and Riparian Habitat Advisory Council). 1989. Upper Sacramento River fisheries and riparian habitat management plan. Report prepared for the California Resources Agency by the Advisory Council established by SB 1086. 158 pp.

Beak Consultants. 1989. Historical channel stability analysis and assessment of spawning gravels in the Lower Yuba River, California. Appendix C to Yuba River Fisheries Investigations, 1986-1988. Beak Consultants, Sacramento CA.

Borland, W.M., and C.R. Miller. 1960. Sediment problems of the Lower Colorado River. Journal Hydrualics Division, American Society of Civil Engineers. HY4:61-88.

Brune, G.M. 1953. The trap efficency of reservoirs. Transactions of the American Geophyscial Union. 34:407-418.

Buel, B. 1980. Effects of Los Padres Reservoir silt release. Unpublished memo, Monterey Peninsula Water Management District, Monterey CA.

Buer, K. 1981. Klamath and Shasta Rivers spawning gravel enhancement study. DWR (California Department of Water Resources), Northern District, Red Bluff. March 1981.

CACSST (California Advisory Committee on Salmon and Steelhead Trout). 1988. Restoring the balance: 1988 Annual Report. CACSST, Sausalito CA.

Calaveras County Water District. 1985. Environmental impact report for hydroelectric development, North Fork Stanislaus River. Sonora, CA.

Collins, B.C., and T. Dunne. 1990. Fluvial geomorphology and river gravel mining: a guide for planners, case studies included. CDMG (California Division of Mines and Geology) Special Publication 98. CDMG, Sacramento CA.

DWR (California Department of Water Resources). 1988. Dams within the jursidiction of the state of California. DWR Bulletin 17-88.

DSD (Division of Safety of Dams, California Department of Water Resources). 1991. Statutes and regulations pertaining to supervision of dams and reservoirs. DSD, Sacramento CA.

DWR (California Department of Water Resources). 1980. Upper Sacramento River Spawning Gravel Study. DWR Northern District, Red Bluff.

DWR (California Department of Water Resources). 1982. Feather River Spawning Gravel Baseline Study. DWR Northern District, Red Bluff.

DWR (California Department of Water Resources). 1983. Monitoring Spawning Habitat, Feather River, California. DWR Northern District, Red Bluff.

Dames & Moore. 1991. Cache Creek aggregate resources mining activities and policy alternatives. Draft program, environmental impact report. Unpublished report submitted to County of Yolo, May 1991.

Dendy, F.E., and W.A. Champion. 1973. Summary of reservoir sediment deposition surveys made in the United States through 1970. USDA Miscellaneous Pulication 1266.

Dendy, F.E., and W.A. Champion. 1978. Sediment deposition in U.S. reservoirs: Summary of data reported through 1975. USDA Miscellaneous Pulication 1362. wrca 22.6 39-1 1981–[illegible]

Denton, D.N. 1986. Clear Creek fishery study. unpublished report. DWR (California Department of Water Resources), Northern District, Red Bluff CA. March 1986.

Denton, D.N. 1991. Sacramento River gravel restoration project porogress report. Unpublished report. DWR (California Department of Water Resources), Northern District, Red Bluff CA. January 1991.

EBASCO Environmental. 1989. Continued monitoring report for 1988/1989 for the cleanup and abatement of sediments sluiced from Our House Reservoir, Middle Yuba River. unpublished report to YWCA (Yuba County Water Agency). EBASCO Environmental, Sacramento CA.

Emmett, W.W. 1980. A field calibration of the sediment-trapping characteristics of the Helley-Smith bed load sampler. U.S. Geological Survey, Prof. Paper, 1139, 44pp.

Environ, Inc. 1980. Draft EIR on sand and gravel operations along Cache Creek between Capay and Yolo: Unpublished report to Yolo County Planning Department, Woodland CA.

Fredericksen, Kamine, and Associates. 1980. Proposed Trinity River Basin fish and wildlife management program. unpublished report to US Water and Power Resources Service (as USBR was then called).

Gardiner, J.L. 1988. Environmentally sound river engineering: examples from the Thames Catchment. Regulated Rivers. 2:445-469.

Gardiner, J.L. 1990. Influences on the development of river catchment planning in the Thames Basin. Ph.D. thesis in Geography, University of Southampton, England.

Gregory, K.J. 1987. River channels. in Human activity and environmental processes. John Wiley & Sons, Ltd., Chichester, England. p.207-235.

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

Hack, H.P. 1986. Design and calculation of reservoirs of run of river stations incorporating sedimentation. in W. Bechteler, ed., Transport of suspended solids in open channels, proceedings of Euromech 192. Munich, Germany. June 11-15, 1985.

Hallock, R.J. 1987. Sacramento River system salmon and steelhead problems and enhancement opportunities. unpublished report to CACSST.

Harrison, A.S. 1950. Report on special investigation of bed sediment segregation in a degrading bed. California Institute of Engineering Research Series. v.33:1.

Hathaway, G.A. 1948. Observations on channel changes, degradation, and scour below dams. in Report on Second Meeting of the International Association of Hydraulic Research. Stockholm, June 1948. p.267-307.

Hazel, C., S. Herrera, H. Rectenwald and J. Ives. 1976. Assessment of effects of altered stream flow characteristics on fish and wildlife. Part B: California Case Studies. Report by Jones and Stokes, Inc. to US Dept. of Interior, Fish and Wildlife Service.

Kellerhals, R., and D. Gill. 1973. Observations and potential downstream effects of large storage projects in northern Canada. in Transactions of the Eleventh International Congress of Large Dams, Madrid, Spain. v. 1, International Commission on Large Dams. Paris. p. 731-754.

King, N.G. 1961. An example of channel aggradation induced by flood control. US Geological Survey Professional Paper 424B, p. 29-32.

Knott, J.M. and C.A. Dunnam. 1969. Sedimentation in Upper Stony Creek Basin, eastern flank of the Coast Ranges of northern California. US Geological Survey Water-Supply Paper 1798-F.

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. 1986. Reconnaissance-level study of sediment conditions in the South Fork Feather River and Slate Creek, Yuba and Plumas Counties. unpublished report to Envirosphere Company, Sacramento CA.

Kondolf, G.M. 1988. Salmonid spawning gravels: a geomorphic perspective on their size distribution, modification by spawning fish, and criteria for gravel quality. PhD. Diss., Johns Hopkins University, Baltimore, MD. 396 pp.

Kondolf, G.M., and W.V.G. Matthews. 1990. Assessment of potential impacts of Monterey Peninsula Water Supply Project ondownstream channel geomorphology of the Carmel River. unpublished report to the Monterey Peninsula Water Management District, Monterey CA.

Kondolf, G.M. and M.J. Sale. 1985. Application of historical channel stability analysis (HCSA) to instream flow studies. Proceedings of the Symposium on Small Hydropower and Fisheries. American Fisheries Society, Bio-Engineering Section and Western Diversion, May 1-3, 1985, Denver, CO. pp. 184-194.

Leopold, L.B., M.G. Wolman and J.P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman Co. San Francisco, CA. 522 pp.

Lisle, T.E. 1989. Sediment transport and resulting deposition ni spawning gravels, north coastal California. Water Resources Research, Vol. 25, no. 6, pp. 1303-1319.

Mahmood, K. 1987. Reservoir sedimentation: Impact, extent, and mitigation. World Bank Technical Paper Number 71. The World Bank, Washington D.C. 118 pp.

Matthews, W.V.G. 1983. Discharge and sediment load for tributaries to the Carmel River. MPWMD Carmel River Watershed Management Plan Working Paper Number 5, October 1983

Matthews, W.V.G. 1987. Evaluation of the effects of the feasible New San Clemente Project alternatives on the channel stability and sediment transport of the Carmel River. Monterey Peninsula Water Management District (MPWMD) Technical Memorandum 87-13. MPWMD, Monterey CA.

Matthews, W.V.G. 1988. Evaluation of reservoir sedimentation rates in the Upper Carmel River watershed. Monterey Peninsula Water Management District Technical Memorandum 88-03. MPWMD, Monterey, CA.

Matthews, W.V.G. 1990. Design of restoration projects on gravel-bed rivers emphasizing the reestablishment of riparian vegetation. unpublished M.S. thesis, University of California Santa Cruz, Santa Cruz, CA.

Matthews and Associates. 1991. Hydrology, geomorphology, and historic channel changes of San Simeon Creek, San Luis Obispo County, California. unpublished report to Cambria Community Services District, Cambria, CA.

Milhous, R.T. 1982. Effect of sediment transport and flow regulation on the ecology of gravel-bed rivers. in R.D. Hey, J.C. Bathurst, and C.R. Thorne, eds., Gravel-Bed Rivers., John Wiley & Sons, Chichester, England. p.819-842.

Miller, G.T. 1990. Living in the environment. 6th edition. Wadsworth Pbulishing Co., Belmont CA.

PG&E (Pacific Gas and Electric Co.). 1970. Sluicing reservoir outlets. Bulletin No. 26, Hydro Generation Electric Operations Division, PG&E, San Francsico CA.

PG&E (Pacific Gas and Electric Co.). unpublished data describing reservoirs and diversions for hydrogeneration projects.

Parfitt, D. and K. Buer. 1980. Upper Sacramento River spawning gravel study. California Department of Water Resources, Northern District, Redding, CA.

Petts, G.E. 1984. Impounded rivers. John Wiley and Sons, Chichester. 325 pp.

Point Reyes Light 1991. Vol. 5, no. 38, Nov. 7, 1991.

Ramey, M.P., and S.M. Beck. 1990. Flushing flow evaluation: the North Fork of the Feather River below Poe Dam. Environment, Health, and Safety Report 009.4-89.9. Pacific Gas and Electric Company, Department of Research and Development, San Ramon CA.

Reiser, D.W., M.P. Ramey, and T.A. Wesche. 1988. Flushing flows. Chapter 4 in Alternatives in regulated river management. CRC Press, Boca Raton FL. p.91-135.

Richards, K. 1982. Rivers: form and process in alluvial channels. Methuen, London, UK. 358 pp.

Sandecki, M. 1989. Aggregate mining in river systems. California Geology, vol. 42, no. 4, pp. 88-94.

Simons, Li, and Associates. 1983. Hydraulic, erosion and sedimentation study of the Santa Clara River, Ventura County, California. unpublished report to Ventura County Flood Control

District, Ventura, CA.

Swanson, M.L. and G.M. Kondolf. 1991. Geomorphic study of bed degradation in Stony Creek, Glenn County, California. Report to California Dept. of Transportation, Division of Structures, 30 June 1991.

USACE (US Army Corps of Engineers). 1979. New Melones Dam and Lake, Stanislaus River, California: Report on reservoir regulation and flood control. unpublished report, USACE, Sacrmento District.

USACE (US Army Corps of Engineers). 1981a. Camanche Dam and Reservoir, Mokelumne River, California: Water control manual. Appendix II to master manual of reservoir regulation, San Joaquin River Basin, California. USACE, Sacramento District. September 1981.

USACE (US Army Corps of Engineers). 1981b. New Exchequer Dam and Reservoir, Merced River, California: Water control manual. Appendix VII to master water control manual, San Joaquin River Basin, California. USACE, Sacramento District. October 1981.

USACE (US Army Corps of Engineers). 1983. New Hogan Dam and Lake Calaveras River, California: Water Control Manual. USACE Sacramento District. Appendix III to master water control manual, San Joaquin River Basin, California. USACE, Sacramento District. June 1983..

USACE (US Army Corps of Engineers). 1987. Black Butte Dam and Lake, Stony Creek, California: Water control manual. Appendix III to master water control manual, Sacramento River Basin, California. USACE, Sacramento District. May 1987.

USACE (US Army Corps of Engineers). 1989a. Mokelumne River, California: 1% Flood at Franklin Road hydrology. unpublished report. USACE, Sacramento District. May 1989.

USACE (US Army Corps of Engineers). 1989b. New Don Pedro Lake, Tuolumne River, California: Water control manual. Appendix VI to master water control manual, San Joaquin River Basin, California. USACE, Sacramento District. September 1989.

USACE (US Army Corps of Engineers). 1990a. American River and Sacramento Metro investigations, California, hydrology office report. unpublished report. USACE, Sacramento District. January 1990.

USACE (US Army Corps of Engineers). 1990b. Bear and Yuba River Basins, California, discharge-frequency relationships. unpublished report to the USACE Sacremento District prepared by the USACE Hydrologic Engineering Center. Project report

No. 90-4. June 1990.

USACE (US Army Corps of Engineers). 1991. Draft feasibility report, American River watershed investigation, California, documentation report. unpublished report. USACE Sacramento District, South Pacific Division. April 1991.

USBR (US Bureau of Reclamation). 1975. Report on standard project flood and intermediate regional flood determination, upper Trinity River basin, Trinity County, California.

USGS. Water Resources Data for California. Various years.

US Bureau of Sport Fisheries and Wildlife. 1968. Fish and wildlife resources of the Klamath River drainage, Oregon and California, with brief comments relating to the Eel, Mad and Smith Rivers. unpublished. 20 pp.

Vanoni, V., ed. 1975. Sedimentation engineering. American Society of Civil Engineers, New York. 745 pp.

Warner, R.F. 1981. The impacts of dams and weirs on the Hawkesbury-Nepean River System, New South Wales, Australia. paper presented to the Second INternational Conference on Fluvial Sediments, University of Keele, UK, September 1981.

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

Woodward-Clyde Consultants, Inc. 1976. Aggregate extraction management study, Yolo County, CA. Report to the County of Yolo Planning Department, Woodland, CA, 128 pp.

Yeend, W.. 1974. Gold-bearing gravel of the ancestral Yuba River, Sierra Nevada, CA. U.S. Geological survey Prof. Paper, 772.

Table 1. Abbreviations Used in this Report

Agencies

CalTrans	California Department of Transportation
CDFG	California Department of Fish and Game
CDMG	California Division of Mines and Geology
CDPR	California Department of Parks and Recreation
CRSA	Carmel River Steelhead Association
DSD	California Deptartment of Water Resources, Division of Safety of Dams
DWR	California Department of Water Resources
EBMUD	East Bay Municipal Utilities District
LADWP	City of Los Angeles Department of Water and Power
MID	Modesto Irrigation District
MMWD	Marin Municipal Water District
MPWMD	Monterey Peninsula Water Management District
NCPA	Northern California Power Agency
PG&E	Pacific Gas and Electric Company
SCE	Southern California Edison
SCS	Soil Conservation Service (U.S. Department of Agriculture)
SCVWD	Santa Clara Valley Water District
SCWA	Sonoma County Water Agency
SFWD	San Francisco Water District
SMARA	Surface Mine and Reclamation Act
SSWD	South Sutter Water District
TID	Turlock Irrigation District
TU	Trout Unlimited
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
YCWA	Yuba County Water Agency

Units of Measure

ac-ft, AF	acre-feet
cfs	cubic feet per second
D50	median sediment grain size (mm)
D84	size (mm) of which 84% of grains are finer
ft	feet
km	kilometer
m	meter
mm	milimeter
mi	mile
yd	yard
yr, y	year

Table 1. Abbreviations Used in this Report (cont.)

Miscellaneous

ab	above
appx	approximately
bel	below
ck	creek
DA	drainage area
na	not applicable
nd	no data
N Fk, S Fk	North Fork, South Fork
nr	near
nya	not yet available
p	present
pers. comm.	personal communication
Q	water discharge or flow
QMax	peak discharge
R	river
RI	recurrence interval
RM	river mile
trib	tributary

Table 2. Inventory of Dams for Selected Basins

River Basin	Major Lowermost Dam	DA (mi^2)	Original Capacity (AF)	RM of Dam	% Basin Blocked	Number of DSD reservoirs in system (a)	Number of PG&E (non-DSD) dams in system (b)	Total Reservoir Capacity in basin (AF)
Merced	New Exchequer	1,037	1,024,000	62.5	81.7	8	---	1,044,485
Tuolumne	Don Pedro	1,533	2,030,000	54.8	81.8	27	---	2,710,848
	LaGrange		500	52.2				
Calaveras	New Hogan	363	317,055	44.6	-na-	15	---	331,222
Stanislaus	New Melones	900	2,419,523		90.3	28	12	2,871,647
	Tulloch	986	68,400	60				
Mokelumne	Camanche	619	430,300	63.6	93.6	29	6	895,300
Cosumnes	no mainstem dams	-na-	-na-	-na-	-na-	-na-	---	
American	Folsom	1,875	1,010,300	-na-	100.0	-nya-	0	
Bear	Camp Far West	285	102,200	-na-	97.6	-nya-	---	
Yuba	Englebright	1,108	70,000	-na-	82.7	-nya-	14	
Feather	Oroville	3,607	2,685,385	68.2 (c)	99.0	-nya-	0	
Sacramento	Shasta	6,421	4,436,400	302.1 (d)	40.6	-nya-	---	
Clear Creek	Whiskeytown	200	241,088	16.5	84.0	1	---	241,088
Trinity	Trinity	692	2,427,700	112 (e)	25.2	2	---	2,442,400
Stony Creek	Black Butte	738+/-	160,000	24.8	95.5	2	---	258,300

(a) as listed in DWR Bulletin 1984
(b) from PG&E records only
(c) river mile at Thermalito Div. Dam
(d) river mile at Keswick Dam
(e) river mile at Lewiston Dam

Table 3. Merced River Basin: Inventory of DSD-Regulated Dams

Dam	Stream	Capacity (ac-ft)	Year Closed	Drainage Area (sq mi)
Mainstem				
McMahon	Maxwell Creek	520	1957	18.200
McSwain	Mainstem	9,730	1966	1,037.000
Merced Falls	Mainstem	620	1901	1,040.000
New Exchequer	Mainstem	1,032,000	1967	1,030.100
Crocker Diversion	Mainstem	300	1910	1,045.000
Kelsey	Trib Dry Creek	1,000	1929	1.140
North Fork				
Green Valley	Smith Creek	240	1957	0.590
Metzger	Dutch Creek	75	1956	1.000
Total Dams: 8	Total Capacity:	1,044,485 ac-ft		

Source: DWR 1988

Table 4. Tuolumne River Basin: Inventory of DSD-Regulated Dams

Dam	Stream	Capacity (ac-ft)	Year Closed	Drainage Area (sq mi)
Mainstem				
Big Creek	Big Creek	7,650	1969	25.600
Bigelow Lake	East Fk Cherry Creek	470	1931	0.600
Brentwood Park	Trib Sullivan Creek	80	1964	0.500
Cherry Valley	Cherry Creek	268,000	1956	114.000
Dawson Lake	Trib Tuolumne River	960	1896	12.600
Don Pedro	Mainstem	2,030,000	1971	1,542.000
Early Intake	Mainstem	115	1925	488.000
Gatzman	Trib Dry Creek	77	1956	0.160
Grinding Rock	Trib Turnback Creek	235	1979	0.200
Groveland Wastewater	Trib Big Creek	100	1981	0.150
High Emigrant Lake	N Fk Cherry Creek	67	n/a	0.500
Kilmer	Trib Dry Creek	99	n/a	0.600
Kincaid	Trib Curtis Creek	50	1860	0.500
La Grange	Mainstem	500	1894	1,548.000
Lake Eleanor	Eleanor Creek	27,800	1918	79.000
Lower Buck Lake	Buck Meadow Creek	360	1931	5.800
Middle Cooperstown	Trib Dry Creek	91	1947	0.890
Moccasin Lower	Moccasin Creek	505	1930	25.900
Modesto Reservoir	Trib Tuolumne River	29,000	1911	10.000
O'Shaughnessy	Mainstem	340,000	1923	459.000
Phoenix	Sullivan Creek	455	1880	24.400
Priest	Rattlesnake Creek	2,350	1923	1.040
Quartz	Trib Woods Creek	1,500	1978	0.117
Railroad Flat No. 2	Trib Dry Creek	95	1945	0.330
San Diego Reservoir	Trib Mormon Creek	40	1860	0.060
Tuolumne Log Pond	Turnback Creek	120	1912	10.000
Twain Harte	Trib Sullivan Creek	129	1928	1.040

Total Dams: 27 Total Capacity: 2,710,848 ac-ft

Source: DWR 1988

Table 5. Calaveras River Basin: Inventory of DSD-Regulated Dams

Dam	Stream	Capacity (ac-ft)	Year Closed	Drainage Area (sq mi)
Mainstem				
Davis No. 2	Trib Calaveras River	1,400	1955	7.800
Foothill Ranch	Trib Calaveras River	100	1952	0.900
Bevanda	Trib Calaveras River	90	1925	0.970
New Hogan	Mainstem	325,000	1963	363.000
North Fork				
Bingham	Rich Gulch	775	1882	2.500
Jeff Davis	Trib Wet Gulch Creek	1,800	1973	0.400
Pine Peak No. 4	Trib North Fork	73	1955	0.100
Reid	Esperanza Creek	70	1969	1.980
South Fork				
Calaveras Cement	South Fork	57	1926	174.000
Cherokee	Cherokee Creek	630	1959	4.900
Christensen No. 1	Steele Creek	69	1951	1.400
Emery	McKinney Creek	630	1850	0.620
Ross	French Gulch Creek	85	1895	1.320
Tanner	Trib San Antonio Creek	124	1959	2.520
White Pines	San Antonio Creek	262	1970	11.800
Total Dams: 15	Total Capacity:	331,222 ac-ft		

Source: DWR 1988

Table 6. Stanislaus River Basin: Inventory of DSD-Regulated Dams

Dam	Stream	Capacity (ac-ft)	Year Closed	Drainage Area (sq mi)
Mainstem				
Andrew Cademartori	Trib Angels Creek	142	1983	0.050
Copperopolis	Penney Creek	225	1905	1.400
Forest Meadows	Angels Creek	108	1975	0.430
Goodwin	Mainstem	500	1912	975.000
Holman	Trib Angels Creek	250	1976	0.060
McCarty	Trib Johnny Creek	93	1938	0.570
Murphys Afterbay	Trib Angels Creek	40	1953	2.800
Murphys Forebay	Trib Angels Creek	54	1953	0.004
Murphys Wastewater	Trib Six-Mile Creek	140	1980	0.100
New Melones	Mainstem	2,400,000	1979	900.000
Rodden Lake	Lesnini Creek	380	1916	1.630
Stanislaus Forebay	Trib Stanislaus River	320	1908	0.100
Tulloch	Mainstem	68,400	1958	971.000
North Fork				
Alpine	Silver Creek	4,600	1906	5.100
Bear Vly Sewage Hldg	Trib Bloods Creek	346	1975	0.100
Fly-In Acres	Moran Creek	100	1953	2.450
Hunters	Mill Creek	200	1928	12.500
Reba	Trib Bloods Creek	240	1965	0.770
Spicer Meadows	Highland Creek	189,000	1988	44.000
Union	N Fork	2,000	1902	15.000
Utica	N Fork	2,400	1908	15.000
Middle Fork				
Beardsley	Middle Fork	97,500	1957	310.000
Beardsley Afterbay	Middle Fork	320	1958	305.000
Donnells	Middle Fork	64,500	1958	226.000
Leland Meadows	Leland Creek	79	1978	0.370
Relief	Relief Creek	15,122	1910	25.000
South Fork				
Lyons	South Fork	6,228	1932	67.800
Main Strawberry	South Fork	18,600	1916	27.000
Total Dams: 28	Total Capacity:	2,871,647 ac-ft		

Source: DWR 1988

Table 7. Mokelumne River Basin: Inventory of DSD-Regulated Dams

Dam	Stream	Capacity (ac-ft)	Year Closed	Drainage Area (sq mi)
Mainstem				
Beggs	Trib Mokelumne River	81	1971	0.097
Camanche	Mainstem	431,500	1963	619.000
Mine Run	Mine Run Creek	31	1979	0.700
Mokelumne Hill	Trib Mainstem	52	1973	0.010
Pardee	Mainstem	210,000	1929	575.000
Woodbridge Diversion	Mainstem	2,464	1910	667.000
Dry Creek				
Arroyo Seco	Trib Dry Creek	2,433	1957	0.440
Goffinet	Jackass Creek	197	1954	1.350
Hamel	Trib Dry Creek	350	1957	0.730
Henderson	Jackass Creek	500	1923	1.000
Jackson Creek	Jackson Creek	22,000	1965	58.000
John Orr	Trib Jackson Creek	152	1959	0.850
Lake Tabeaud	South Fork Jackson Creek	1,170	1901	0.750
Preston	Trib Mile Creek	268	1949	0.120
Preston Forebay	Trib Sutter Creek	30	1892	---
Sand Plant	South Fork Merchant Creek	414	1962	0.125
North Fork				
Lower Bear River	Bear River	52,025	1952	37.000
Lower Highland	North Fork	175	1900	0.500
Lower Blue Lake	Blue Creek	4,300	1903	4.800
Meadow Lake	Meadow Creek	5,850	1903	5.500
Salt Springs	North Fork	139,400	1931	169.000
Tiger Creek Afterbay	North Fork	3,960	1931	360.000
Tiger Creek Reg	Tiger Creek	540	1931	9.000
Tiger Creek Forebay	Tiger Creek	36	1931	---
Twin Lakes	Meadow Creek	1,300	1901	0.800
Upper Blue Lake	Blue Creek	7,500	1901	2.700
Upper Bear River	Bear River	6,756	1900	28.000
Middle Fork				
Middle fork	Middle Fork	1,718	1939	28.500
West Point Reg	Ruse Creek	50	1965	0.300

Total Dams: 29 Total Capacity: 895,252 ac-ft

Source: DWR 1988

Table 8. Reservoir Sedimentation, Sierran Drainages

		Drainage Area (mi^2)			Sed. Yield (AF/mi^2/y)		Capacity (AF)				
Reservoir	Stream	Total	Contrib.	Period	Total	Contrib.	Orig.	Last Survey	Capacity Loss %	Remarks	Source
Lake McClure	Merced R	1037	1022	1926-1946	0.18 0.167	0.18	289,000	285,646	1.2	Enlarged in 1967 to 1,032,000 AF	USACE (1990a) reported 0.18; Dendy & Champion (1973) reported 0.167
Don Pedro	Tuolumne R	1533	1001	1923-1945	0.21	0.32	289,000	284,266	1.6	Enlargement completed 1971 to 2,030,000 AF	Dendy & Champion 1973
Pardee	Mokelumne R	575	387	1929-1943	0.15	0.22	210,000	209,183	0.4	Excludes areas above Salt Spring & Bear River Reservoir	USACE 1990a
Bullards Bar	N. Yuba R	481	479	1919-1939	0.28	0.28	31,500	28,893	8.3	Enlargement completed 1970 to 969,600 AF	USACE 1990a
Combie	Bear R	130	129	1928-1935	0.75	0.75	8,545 5,555	7,840	8.3		USACE 1990a
New Melones	Stanislaus R	900		?	0.13	nya	2,419,523			unknown method of computation	
Oroville	Feather R	3607		?	0.2(a)	nya	2,685,385			unknown method of computation	USACE 1990a
Auburn	American R	974	449	NA	0.27(a)	0.59	600,000	-na-		Under Construction; estimate from USBR based on sed. sampling	USACE 1990a
La Grange	Tuolumne R	1501	1501	1895-1905	0.083	0.083	2,332	1,068	54.2	First Don Pedro built just upstream in 1923	

Table 9. Reservoir Sedimentation, Coast Range Drainages

		Drainage Area (mi^2)			Sed. Yield ($AF/mi^2/y$)		Capacity (AF)				
Reservoir	Stream	Total	Contrib.	Period	Total	Contrib.	Orig.	Last Survey	Capacity Loss %	Remarks	Source
Black Butte	Stony Ck	738	440	1963-1984	1.04	1.74	160,000	143,800	10.1		Swanson and Kondolf 1991
East Park	Stony Ck	102	102	1910-1962	0.37	0.37	50,900	48,940	3.9		Knott & Dunnan 1969
Stony Gorge	Stony Ck	301	199	1928-1962	0.27	0.41	50,000	48,160	3.7		Knott & Dunnan 1969
Matanzas	Matanzas	11	11	1963-1982	0.79	0.79					SCWA 1991
Scott	Eel R	288		1921-1984	0.83		94,400	80,700	14.5		SCWA 1991
Coyote	Russian R	105		1952-1985	0.93		91,800	88,580	3.4		SCWA 1991
Los Padres	Carmel R	44.9	44.9	1949-1984	0.79	0.79	3,100	1,930	37.7	Large fire in 1977 contributed 500+ AF in 1978	Matthews 1988
San Clemente	Carmel R	125	80.1	1921-1949	0.14	0.14	1,400	900	35.7	Los Padres built upstream 1949 reduces contributing area. Fire and airstrip construction increased yield 1973-1984.	Matthews 1988
				1949-1973	0.04	0.06	900	775	44.6		
				1973-1984	0.31	0.48	775	316	84.6		

Table 10. Gages Downstream of Major Reservoirs on Selected Rivers

River Basin	USGS Gage #	Gage Location Name	DA, mi^2 (RM)	Period of Record	Avg Q (cfs)	Avg Q (AF)
Merced	11272500	nr Stevinson	1,273 (4.4)	1941-P	691	500,600
	11270900	bel Merced Falls Dam nr Snelling	1,061	1901-P	1,342	972,300
Tuolumne	11290000	at Modesto	1,884 (16.2)	1896, 1941-P	1,385	1,003,000
Calaveras	11308900	bel New Hogan Dam nr Valley Springs	363 (439)	1961-1990	229	165,900
Stanislaus	11303000	at Ripon	1,075 (9.5)	1941-P	1,014	734,600
Mokelumne	11325500	at Woodbridge	661	1929-P	600	434,700
Cosumnes	11335000	at Michigan Bar	536	1908-P	491	355,700
American	11446500	at Fair Oaks	1,888	1905-P	3,741 (a) 3,779 (b)	2,708,000 (a) 2,738,000 (b)
Bear	11424000	nr Wheatland	292	1929-P	417 (c) 404 (d)	301,900 (c) 292,700 (d)
Yuba	11421000	nr Marysville	1,339	1941-P	2,490	1,804,000
Feather	11407000	at Oroville	3,624 (17.3)	1902-P	5,836	4,225,000
Sacramento	11370500	at Keswick	6,468	1929-P	8,376	6,064,000
		at Red Bluff	8,900	1892-P	11,400	8,259,000
Clear Creek	11372000	nr Igo	228	1940-P	413	299,200
Trinity	11525500	at Lewiston	719 (111)	1913-P	1,641	1,189,000
Stony Creek	11388000	bel Black Butte Dam nr Orland	738	1956-1990	635	460,100

(a) Pre-dam period, 1905-1956
(b) Post-dam period, 1956-1990
(c) Pre-dam period, 1930-1963
(d) Post-dam period, 1963-1990

(Source: USGS published records, Water Resources Data for California)

Table 11. Pre-Dam and Post-Dam Flood Peaks for Selected Rivers

PEAK DISCHARGE, ANNUAL MAXIMA[1]

River	Dam	Location of Gage for Computations	Pre-Dam							Post-Dam						
			Q1.5	2	5	10	20	50	100	Q1.5	2	5	10	20	50	100
Merced	New Exchequer	bl McSwain Dam	6,600	10,500	26,000	41,000	62,000	98,000	135,000	1,800	2,200	2,900	5,000	5,500	5,800	6,000
Tuolumne[2]	Don Pedro	nr LaGrange	12,000	13,500	16,000	18,000	19,500	21,500	23,000	400	670	4,800	7,300	8,500	10,000	11,500
Stanislaus	New Melones	at New Melones	6,300	10,300	26,000	43,000	63,000	99,000	135,000	3,100	3,500	7,200	8,000	8,000	8,000	800
Calaveras	New Hogan	bl New Hogan	9,500	12,500	21,500	28,500	36,000	59,000	70,000	1,450	1,950	7,000	8,100	9,000	127,000	12,500
Mokelumne	Comanche	bl Comanche	3,800	5,900	13,500	21,500	31,500	48,500	65,000	1,500	1,900	3,900	5,000	5,100	5,100	20,000
Cosumnes[3]	---	at Michigan Bar	4,500	6,900	14,300	20,200	27,000	37,500	47,000	—	---	no	mainstem	dams	—	---
American[4]	Folsom	at Fair Oaks	20,500	31,000	69,000	105,000	150,000	220,000	285,000	7,800	16,000	68,000	100,000	115,000	115,000	230,000
Bear	Camp Far West	nr Wheatland	8,700	12,000	22,000	30,000	38,000	52,000	62,000	2,900	6,600	20,500	29,500	38,000	52,000	62,000
Yuba[4]	Englebright	bl Englebright	21,000	33,000	82,000	128,000	185,000	280,000	370,000	14,000	21,500	49,000	76,000	100,000	110,000	160,000

---

[1] For sources of data, see Table 12

[2] Pre-dam and post-dam are mean daily flows

[3] Unregulated flows computed from mean daily records

[4] Pre-dam computed from mean daily flows
Post-dam computed from peak discharges

Table 11. Pre-Dam and Post-Dam Flood Peaks for Selected Rivers (cont.)

			Pre-Dam							Post-Dam						
River	Dam	Location of Gage for Computations	Q1.5	2	5	10	20	50	100	Q1.5	2	5	10	20	50	100
Feather	Oroville	at Oroville	37,500	55,000	1105,000	133,000	195,000	265,000	325,000	11,500	19,000	59,000	82,000	127,000	150,000	150,000
Upper Sacramento	Shasta	at Keswick at Red Bluff	nya													
Clear Ck	Whiskeytown		nya													
Trinity	Trinity	at Lewiston	11,400	16,000	31,500	45,000	60,000	84,000	105,000	300	300	1,500	2,700	3,700	5,700	8,400
<u>Coast Range</u>:																
Stony Ck	Black Butte	bl Black Butte	9,000	14,500	32,000	45,000	58,000	78,000	93,000	3,800	10,000	15,000	15,000	15,000	15,000	20,000

Table 12. Ratio of Post-Dam to Pre-Dam Peak Discharge and Maximum Recorded Floods Pre- and Post-Dam

				Ratio of Post-Dam to Pre-Dam Peak Discharge							Recorded QMax (USGS Records)			
River	Dam	Operating Agency	Year of Closure	Q1.5	2	5	10	20	50	100	Pre (Yr)	Post (Yr)	Source	Notes
Merced	New Exchequer	MID	1967	0.27	0.21	0.11	0.12	0.09	0.06	0.04	47,700 (1911)	8,100 (1983)	USACE 1981b	Rainflood
Tuolumne	Don Pedro	TID & MID	1971								57,000 (1950)	13,800 (1983)	USACE 1989b	Mean daily, snowmelt
Stanislaus	New Melones	USBR	1979	0.49	0.34	0.28	0.19	0.13	0.08	0.06	62,500 (1955)	6,620 (1986)	USACE 1979	Rainflood
Calaveras	New Hogan	USACE	1963	0.15	0.16	0.33	0.28	0.25	0.20	0.18	50,000 (1911)	10,000 (1980)	USACE 1983	Rainflood
Mokelumne	Comanche	EBMUD	1963	0.39	0.32	0.29	0.23	0.16	0.11	0.31	27,000 (1950)	5,340	USACE 1981a	Rainflood
Cosumnes	—	—	—	no significant regulation							45,100 (1986)	not regulated	USACE 1989a	Mean daily
American	Folsom	USBR	1956								180,000 (1950)	134,000 (1986)	USACE 1991	Pre=Mean daily, rain; Post=peak
Bear	Camp Far West	SSWD	1963	0.33	0.55	0.93	0.98	1.00	1.00	1.00	35,000 (1955)	48,000 (1986)	USACE 1990b	Rainflood
Yuba	Englebright	USACE	1941	0.67	0.65	0.60	0.59	0.54	0.39	0.43	-na-	171,000 (1964)	USACE 1990b	Rainflood
Feather	Oroville	DWR	1968	0.31	0.35	0.56	0.55	0.65	0.57	0.46	230,000 (1907)	134,000 (1986)	DWR 1982	Rainflood
Upper Sacramento	Shasta	USBR	1945	nya							186,000 (1940)[1] 291,000 (1940)[2]	81,400 (1974)[1] 157,000 (1970)[2]		
Clear Ck	Whiskeytown	USBR	1963	nya							24,500 (1935)	89,200 (1988)		
Trinity	Trinity	USBR	1962	0.03	0.02	0.05	0.06	0.06	0.07	0.08	71,600 (1955)	14,400 (1974)	USBR 1975	USBR chgd oper. policy after 1974 flood
Stony Ck	Black Butte	USACE	1963	0.42	0.69	0.47	0.33	0.26	0.19	0.22	36,300 (1958)	23,300 (1986)	USACE 1987	Higher release to prevent add'l spill damage in 1986

---

[1] at Keswick

[2] at Red Bluff

Tab. . Channel Incision Below Dams

Stream	Dam	Avg/max incision (ft)	Period	Remarks	Source
Stony Creek	Black Butte	1-3	1963-1990	Reach immed. below dam	Swanson & Kondolf 1991
Carmel River	San Clemente	5+	1947-1982	Complicated due to concurrent response to 1911 flood (100 yr) and 1921 dam construction	Kondolf 1982
Coyote Creek	Leroy Anderson	5 est.	1950-1989		Kondolf & Matthews 1990
Yuba River	Englebright	4	1979-1986	Thalweg incised 4 ft in channel immediately downstream of dam	Beak Consultants 1989

Table 14. Bed Coarsening Below Dams

				Bed MaterialSize			
Stream	Dam	DA (mi^2)	Year of Closure	Pre-Dam	Post-Dam	Source	Remarks
Sacramento River	Shasta[1]	6,421	1945	gravel	boulders, bedrock	Parfitt and Buer, 1980	
Clear Creek	Whiskeytown	200	1963	gravel	cobbles	Denton, 1986	CDFG biologists estimate 93% loss of spawning gravels from 1956 to 1970 in six-mile reach upstream Saeltzer Dam
Klamath River	Iron Gate	4,630	1962	D50: 30-40mm	D50: 40-130mm	Buer, 1981	Former heavily used spawning riffles; assume pre-1962 D50 of 30-40mm had become too coarse for spawning
Trinity River	Trinity/ Lewiston	692	1962	gravel	cobbles	Hazel, et al. 1976, p. 73	Important spawning grounds just below dams scoured out by high flows in 1970 and 1974
Putah Creek	Monticello	576	1957	gravel (1972)	Bedrock, boulders (1983)	Dettman (pers. comm., 1991)	
Feather River	Oroville	3,607	1968			R. Painter, F. Meyer, pers. comm. 1991	No measurements were made, but was considered enough of a problem by resource agencies to go ahead with gravel enhancement
Yuba River	Englebright	1,108	1941	gravel	cobbles, boulders		D50 rapidly increases from 67 mm near Parks Bar bridge to 90 mm at Roase Bar to boulders in narrows downstream of dam
Bear River	Camp Far West			gravel	Hardpan exposed over long reaches		Channel degradation documented at bridge and gage cross sections. Relict gravels on high bars, floodplain, but not in channel.
American River	Folsom/Nimbus	1,875	1956	gravel		Dettman (pers. comm., 1991)	
Carmel River	Los Padres San Clemente	44 121	1947 1921	gravel	boulders	Dettman, 1991	Pre-dam based on material in reservoir deltas and gravels available upstream reservoirs
N Fk American River	North Fork	343	1939	nya	D50=112mm		Pre-dam assumed to have gravel based on material found in reservoir deltas

---

[1] Reregulated by Keswick Dam

Table 14. Bed Coarsening Below Dams (cont.)

Stream	Dam	DA (mi^2)	Year of Closure	Bed MaterialSize		Source	Remarks
				Pre-Dam	Post-Dam		
Silver Branch American River	Silver Lake	14	1876	gravel	bedrock		
Eel River	Cape Horn Scott		1907 1922	gravel	cobbles	Hazel et al, 1976, p. 329	Lack of replenishment & reduced gravel availability below dams and vegetation encroachment
Lagunitas Creek	Peters	22	1954	gravel	cobbles	Point Reyes Light 15:38, Nov. 7, 1991	gravels progressively washed away
San Simeon Creek	---			gravel	Bedrock and hardpan exposed	Matthews & Assoc. 1991	Due to instream gravel mining 2,000-6,000 ft. downstream

Table 15. Examples of Fine Sediment Accumulation in Channel Beds Below Dams

Dam	River	Period	Observations	Source
Lewiston	Trinity	1962-79	fine sediment (<4.76 mm) in reach above Grass Valley Creek averaged 13%, in reach below averaged 28%	Frederiksen, Kamine & Assoc. 1980
			sedimentation destroyed an estimated 80% of salmon spawning habitat in 2-mile reach below Grass Valley Ck (CDFG 1967)	Hazel, et al. 1976
Whiskeytown	Clear Ck	1963-82	fine sediment (<4.0 mm) content averaged ~16.5% in 1965 bed samples, 24% in 1982 samples	Denton 1986
Iron Gate	Klamath	1962-76	accumulated fine sediment observed along with increase in aquatic vegetation	U.S. Bureau of Sport Fisheries & Wildlife 1968
San Clemente	Carmel	1983-1986	fine sediment (<4.0mm) from Tularcitos Ck completely smothered channel for 3 km. Mostly flushed out by subsequent high flows	Matthews 1983; Dettman, pers. comm. 1991
Friant	San Joaquin	1942-1976	siltation & vegetation encroachment greatly reduced spawning gravels	Hazel, et al. 1976
Baum Lake	Hat Ck	1989-1991	possible sources of fine sediments accumulated below reservoir include: (1) fine sediment stored in reservoir transported to downstream reach through piping in volcanic terrain; (2) sediment generated from road washout	
Tulloch/ Goodwin	Stanislaus	1959-1972	siltation and compaction at gravels, encroachment of riparian vegetation, 35% of gravels lost	Hazel, et al. 1976
Ruth	Mad	1961-1976	loss of spawning gravel by sedimentation of fine materials	Hazel, et al. 1976
Isabella	Kern	1955-1976	fine sediment deposits below SCE & PG&E diversions downstream	Hazel, et al. 1976, p 415

Ta . Channel Incision from Instream Gravel Mining

Stream	Avg/max incision (ft)	Period	Remarks	Source
San Simeon Creek	5-7/10	1966-1991	At San Simeon Creek Road, 1st Bridge	Matthews & Associates 1991
Russian River	11.5/18	1940-1972	Below Healdsburg Dam, deep pit mining 1950-60, bar skimming 1960-90	Collins & Dunne 1990
Cache Creek	15/27	1959-1980		Collins & Dunne 1990; Envion 1980; Dames & Moore 1991; CalTrans bridge records
Stony Creek	16	1976-1990	Maximum 16 ft at Highway 32	Swanson & Kondolf 1991; CalTrans bridge records
Putah Creek	8/15	1954-1982	Built 1954; heavy rock placed several times, most recently 1982	CalTrans bridge records
Thomes	4+/-	1965-1975	Built 1965	CalTrans bridge records
Etna	4/8	1959-1987	built 1959	CalTrans bridge records
Clear Creek	>3	1950-1987	Built 1950; incision occurred 1971-1987	CalTrans bridge records
Cottonwood Creek	8-10/>14	1964-1986	Built 1964	CalTrans bridge records
Dry Creek	5/8	1955-1986	Built 1954; built rock dam 1980	CalTrans bridge records
Frasier Creek	6/8	1954-1980	Built 1952; 1966-86 noted degradation and instream mining in vicinity	CalTrans bridge records
Sulphur Creek	4-5/7	1964-1980	Built 1948; bridge washed out 1963; rock check dam installed 1980	CalTrans bridge records
Dibble Creek	5-6/7	1965-1987	Built 1965; rock dam built 1982	CalTrans bridge records
East Sand Slough	6+	1947-1987	Built 1947; rock work 1961, 1966	CalTrans bridge records
Merced River	6/8	1953-1972		CalTrans bridge records
Santa Clara River	16	1957-1968	Partial failure 1979	Simons & Li Assoc. 1981
	add'l 13	1969-1978	Foundations lowered	
Santa Ysabel Creek	>10	1968-1980		CalTrans bridge records

Table 17. A Partial Inventory of Bridge Repair Costs Attributed to Instream Gravel Mining Through 1984

Stream	Highway	Bridge No.	Maximum Degradation (ft)	Dates of Repair	Cost of Repairs	Remarks
Russian River	222	10-80	15	1978-1984	NA	Repeated placement of riprap
Russian River	101	20-69	17	NA	NA	
Kelsey Creek	29	14-64	NA	1969-1983	$ 3,500+	Riprap placement in 1969, 1974, 1983. Cost of 1974 riprap = $3,500.
Putah Creek	29	14-14	NA	1958	6,000+	Riprap, partial cost only
Stony Creek	32	11-29	14	1979-1984	431,000	Extended concrete footings, replaced riprap.
Cache Creek	505	22-101R	19	1970-1982	105,000+	Additional piles and needle pins under piers, riprap
Kaweah River	216	NA	7	1956	58,000	Repair of pier settled 7 ft.
San Diego River	67	57-87, 59-936	NA	1981	3,339,514	Bridge replaced due to extensive undercutting
San Juan Creek	74	55-60	NA	1983	250,000	Grade control, abutment repair
Big Tujunga Wash	210	53-17	NA	1969-1970	571,104	Concrete mattress, substructure protection
So. Branch Big Tujunga Wash	210	53-18	NA	1975	440,000	Bridge replaced
Santa Clara River	118	52-49	NA	1969-1980	732,042	Six spans and footing replaced, footing lowered
Temecula Creek	79	56-188	NA	1980	423,000	Bridge replaced
					$6,360,000	Total does not include all costs involved at these sites, and includes no costs at unlisted sites. With more careful research, this figure would at least double (Ray Hackett, Caltrans, unpub. memo, 1984).

Source: unpub. data in files of California Department of Transportation, Sacramento

Table 18. Gravel Enhancement Projects

Reservoir (Dam)	River	Year	Vol. Emplaced (yd^3)	Cost ($)	Agency	Remarks (source)
Camanche	Mokelumne	1990	100	$ 20,000	EBMUD	(Joe Miyamoto, EBMUD, pers. comm. 1991)
Shasta^1	Sacramento	1979	8,700	-----	CDFG	85% of emplaced gravel (D50=13.5, D84=24mm) was removed by high flows in Jan. and Feb. 1980 (Parfitt & Buer 1980)
Shasta^1	Sacramento	1988	100,000	250,000	CDFG	Gravel placed at mouth of Salt Ck., 1 mi downstream of Keswick Dam, funded by USBR (Denton 1991)
Shasta^1	Sacramento	1989	900,000	200,000	CDFG	Gravel placed at mouth of Salt Ck., 1 mi downstream of Keswick Dam, funded by USBR (Denton 1991)
Shasta^1	Sacramento	1990	16,000	2,200,000	DWR, CDFG	Sacramento R. from Keswick Dam to Clear Ck. Funded by Delta Pumps Fish Protection Agreement 1986 (Denton 1991)
Shasta^1	Sacramento	planned 1991-2000	8,000	19,800,000	DWR, CDFG	Sacramento R., Keswick Dam downstream. Cost based on $\$22/yd^3$. (Denton 1991)
Los Padres	Carmel	1990 1991	40 800	580 82,000	MPWMD, CRSA	Gravel emplaced by CCC hand labor in potential spawning sites (cost does not include sup./planning cost or labor); redistributed by 1991 flood (RI~2 yr) (D. Dettman, MPWMD, pers. comm. 1991)
Iron Gate	Klamath	1985	2,180	136,000	CDFG	Includes costs of channel work including bed excavation of 9,800 yd^3 and boulder placement (R. Painter, CDFG, pers. comm. 1991)
Kent (Peter's)	Lagunitas Ck	1991	54	800	MMWD, tu	Cost does not include value of volunteer labor to emplace gravel, transport, etc. (Newspaper article in Point Reyes Light, Nov. 7, 1991)
Courtwright	N Fk Kings	1989?	nya	nya	PG&E	Helicopter used to drop gravel in narrow gorge by hopper (B. Waters, PG&E, pers. comm. 1989)
Clair Engle (Trinity)^2	Trinity	1989	1,950	22,000	USBR	Gravels emplaced at 5 sites (R. Smith, USBR, pers. comm., 1991)

---

[1] Reregulated by Keswick Dam

[2] Reregulated by Lewiston Dam

Table 18. Gravel Enhancement Projects (con't.)

Reservoir (Dam)	River	Year	Vol. Emplaced (yd^3)	Cost ($)	Agency	Remarks (source)
Folsom[3]	American	1991	1,000	30,000	Sacramento County	Gravels emplaced below Nimbus Dam as mitigation for disruption of spawning beds at Sunrise Ave. bridge (F. Meyer, CDFG, and J. Purvis, Teichert Construction, pers. comm. 1991)
Unnamed	Lee Vining Ck	1991	300	4,500	LADWP	Cost reflects delivered price of gravel (at $\$15/yd^3$ only, does not include planning, design, or placement costs (S. English, pers. comm. 1991)
Grant Lake	Rush Ck	1991	1,200	18,000	LADWP	Cost reflects delivered price of gravel (at $\$15/yd^3$ only, does not include planningg, design, or placement costs (S. English, pers. comm. 1991)
Oroville	Feather	1982	3,000	nya	CDFG,DWR	Gravel emplacement part of larger project involving maintenance of spawning channels and gravel ripping (DWR 1983; F. Meyer, R. Painter, CDFG, pers. comm., 1991)
Oroville	Feather	1987	2,040	nya	CDFG,DWR	Gravel emplacement part of larger project involving maintenance of spawning channels and gravel ripping (DWR 1983; F. Meyer, R. Painter, CDFG, pers. comm., 1991)
Pleasant Valley	Owens	1962	830	nya	LADWP	Gravel imported to artificial spawning channel (Hazel, et al. 1976)

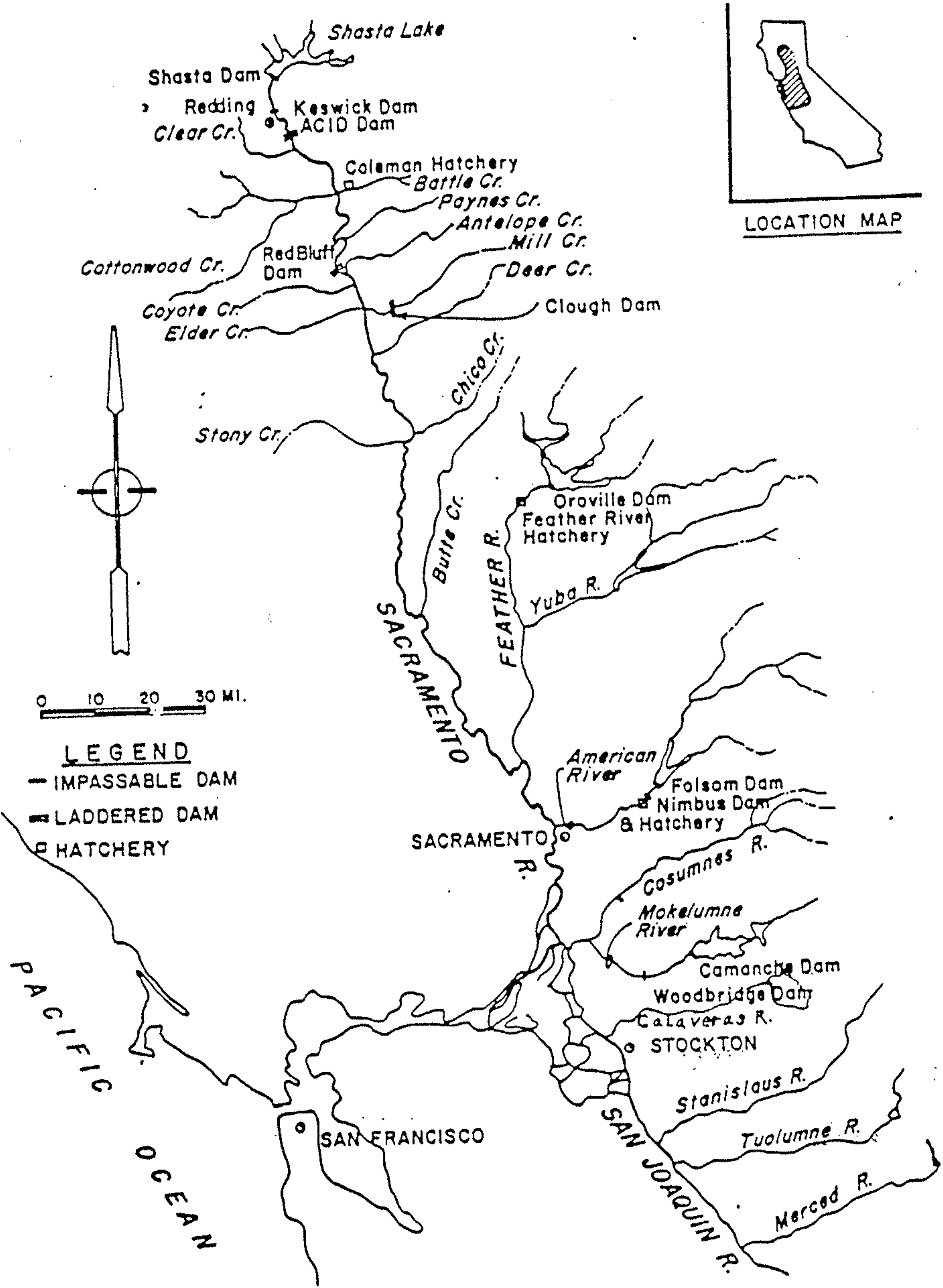
---

[3] Reregulated by Nimbus Dam

Table 19. Artificial Spawning Channels Below Dams

Reservoir /Dam	River	Year	Agency	Project Description (source)
New Exchequer	Merced	1966	MID	Spawning channel constructed downstream of Crocker-Huffman Diversion Dam (Hazel et al 1976, p. 505)
Oroville	Feather	1974	CDFG	Spawning channel known as "Moe's Ditch" constructed. Has required periodic rebuilding after large floods (DWR 1982, DWR 1983)
New Don Pedro	Tuolumne	1973	MID -TID	Spawning channel constructed by grading of stream bed over 57 ac (Hazel et al. 1976, p. 496)
Pleasant	Owens	1962	LADWP	Spawning channel 100 ft long, 15 ft wide (Hazel et al. 1976, pp. 556-557)
Clair Engle /Trinity	Trinity	1987 -90	USBR	Several side channels for spawning and rearing constructed between Lewiston Dam and Grass Valley Ck (A. Hamilton, USFWS, pers. comm., 1991)
Red Bluff Diversion Dam	Sacramento	1971	USBR	3.25-mile spawning channel known as Tehama-Colusa Can Fish Facilities constructed to mitigate for loss of 3,000 adult fall-run chinook salmon; facility operated by USFWS. Numerous problems have plagued the facility (USRFRHAC, 1989)
Keswick	Sacramento	1986 1988	DWR	At two sites, known as Turtle Bay East and West, side channels were enhanced with gravels to create spawning site

Figure 1. Location Map of Principal Study Basins



(Source: Hallock 1987)

Figure 2. Impacts of Large Reservoir Construction and Operation on Resources

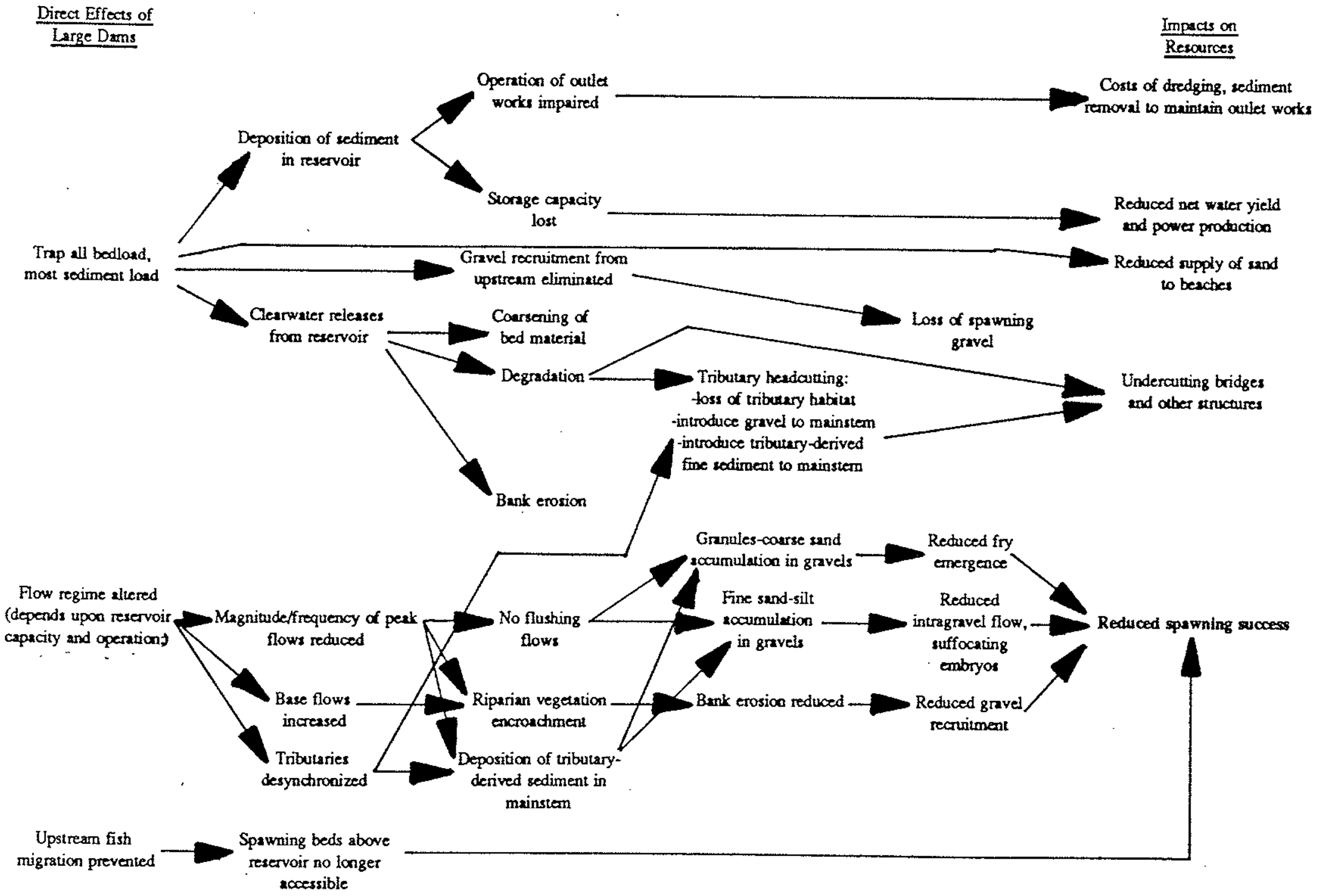


Figure 3. Impacts of Instream Gravel Mining

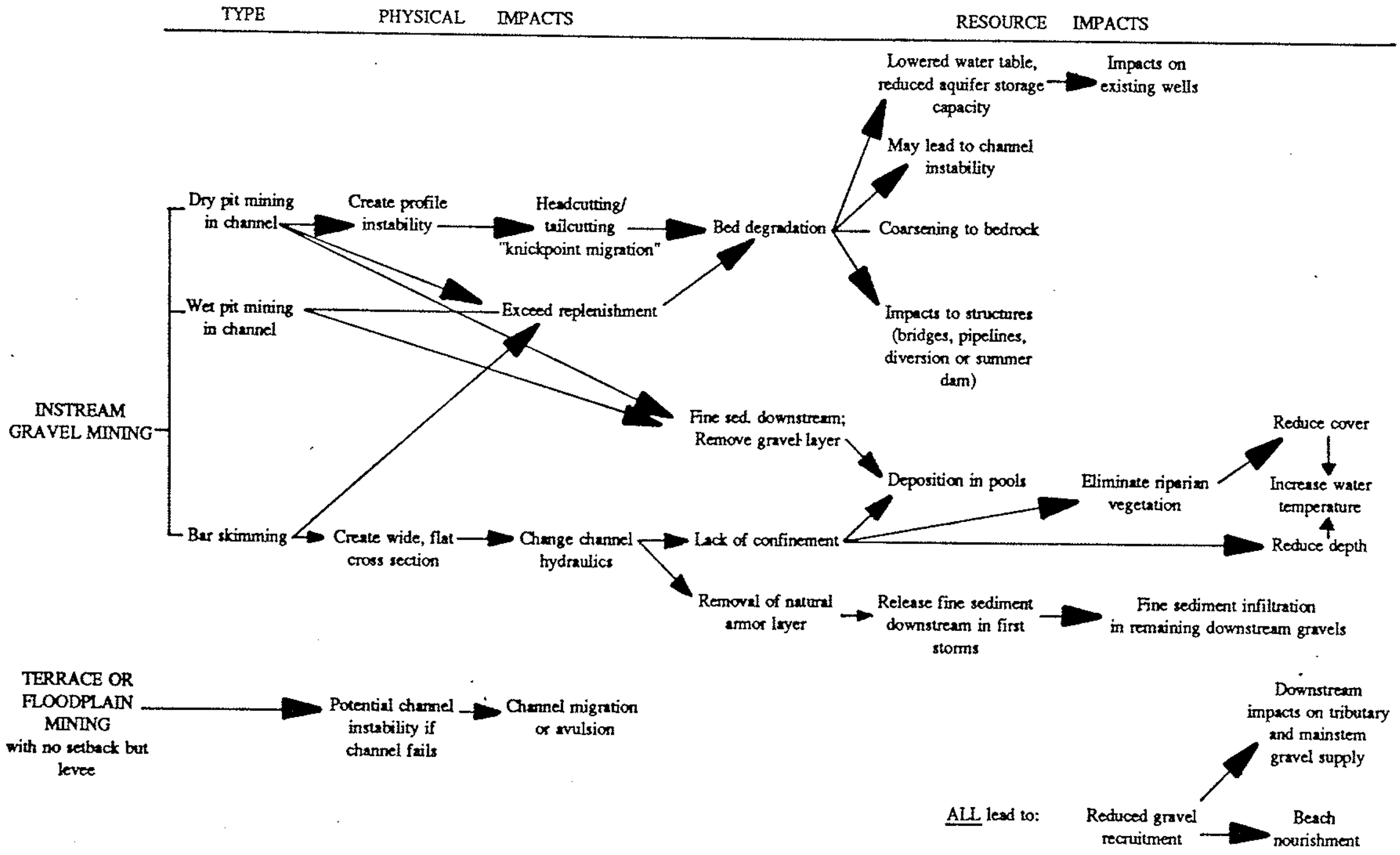


Figure 4. Knickpoint Migration Following Pit Excavation

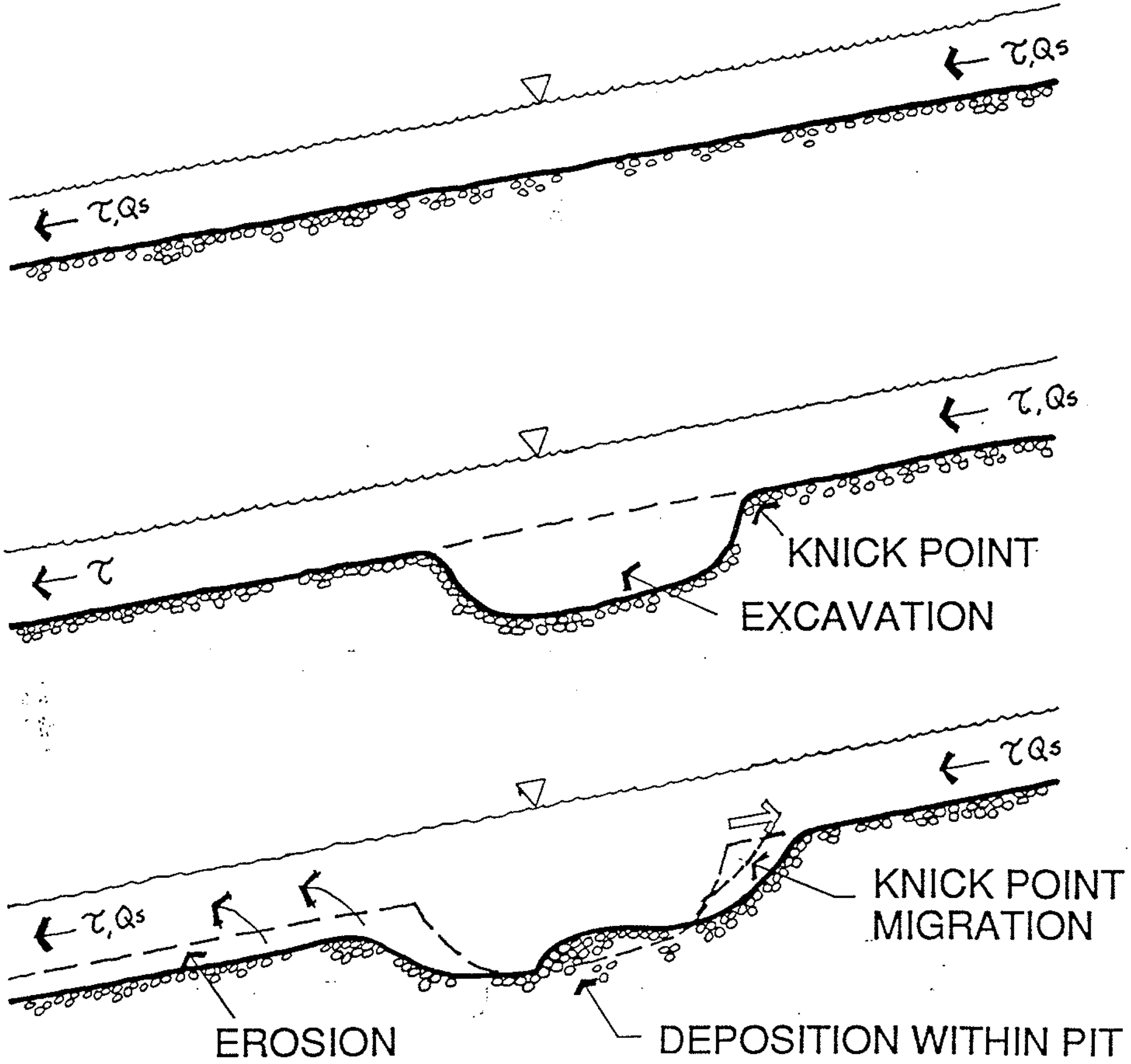
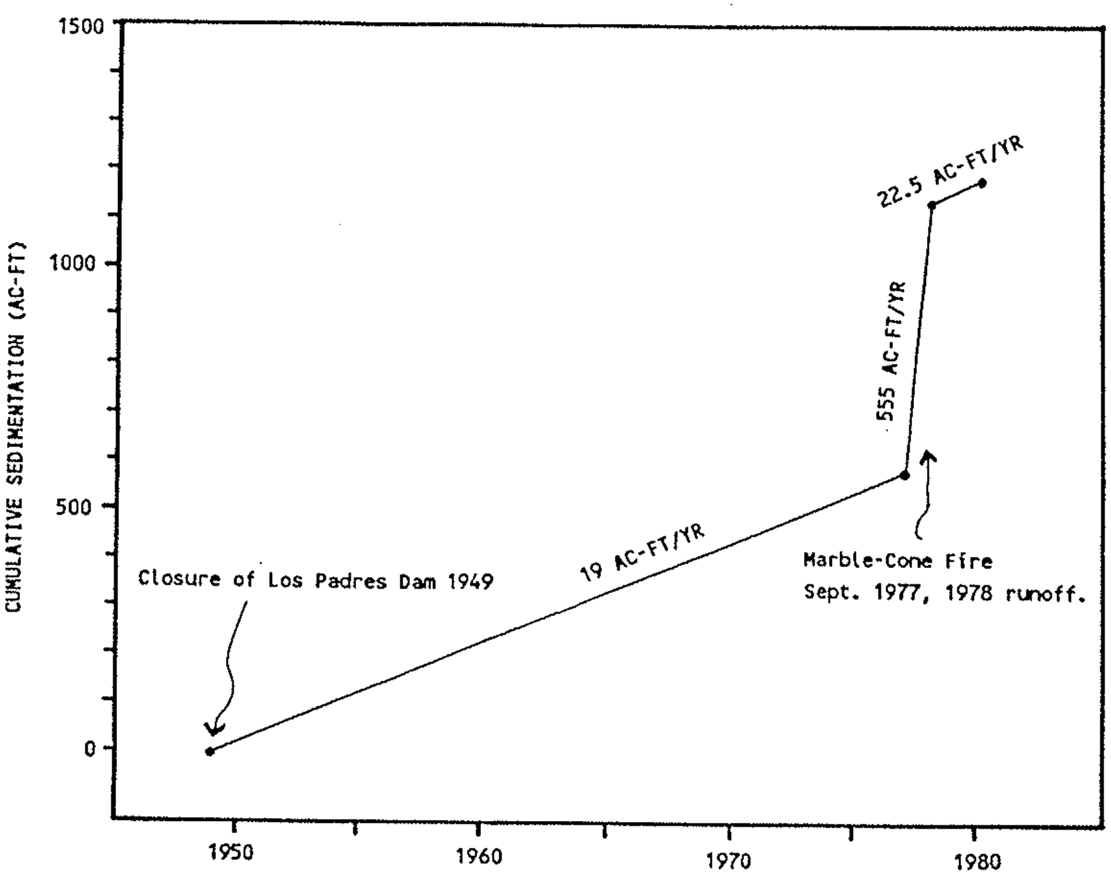
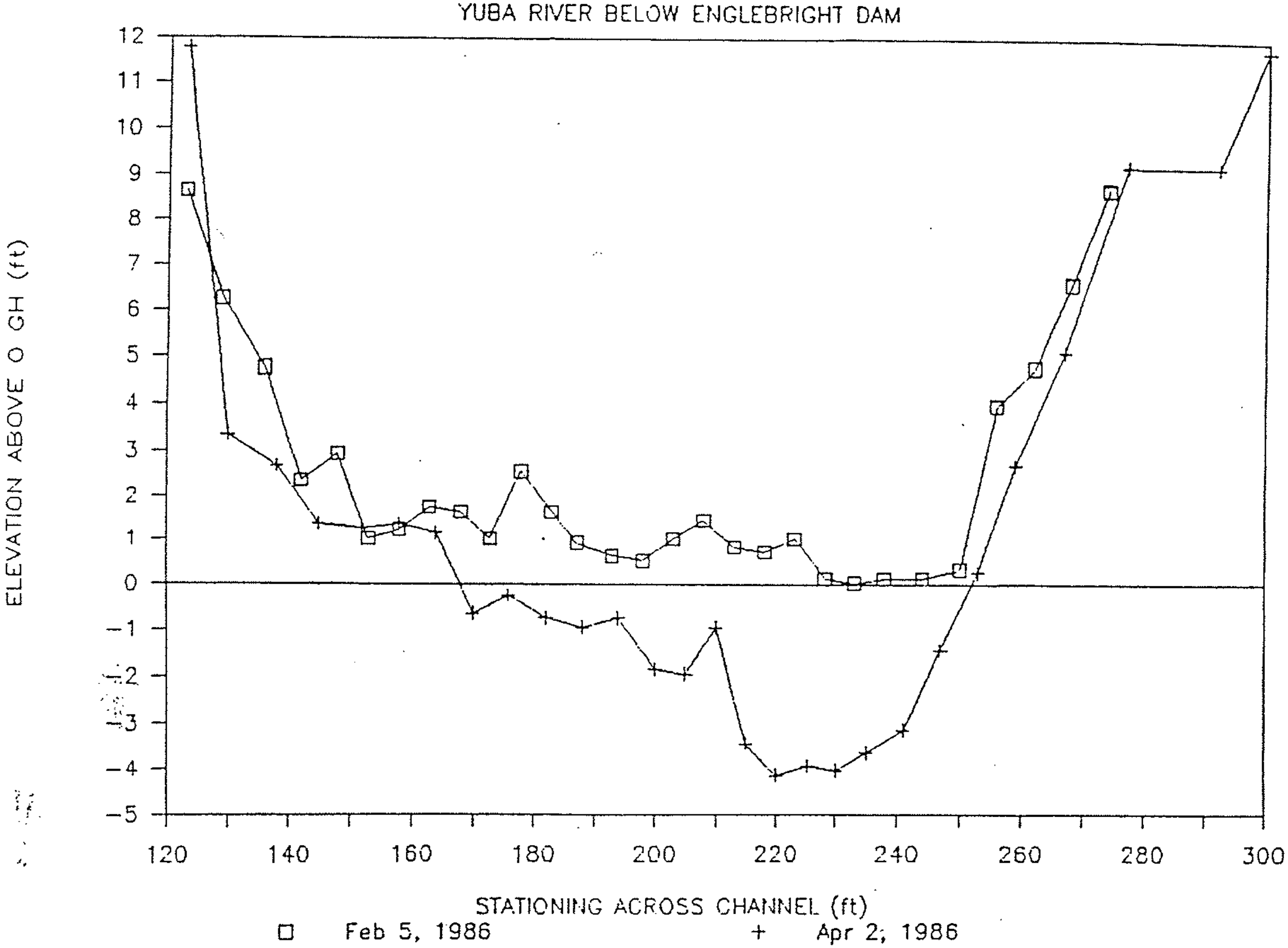


Figure 5. Reservoir Sedimentation in Los Padres Reservoir, Monterey County, 1946-1980



(Source: Matthews 1988)

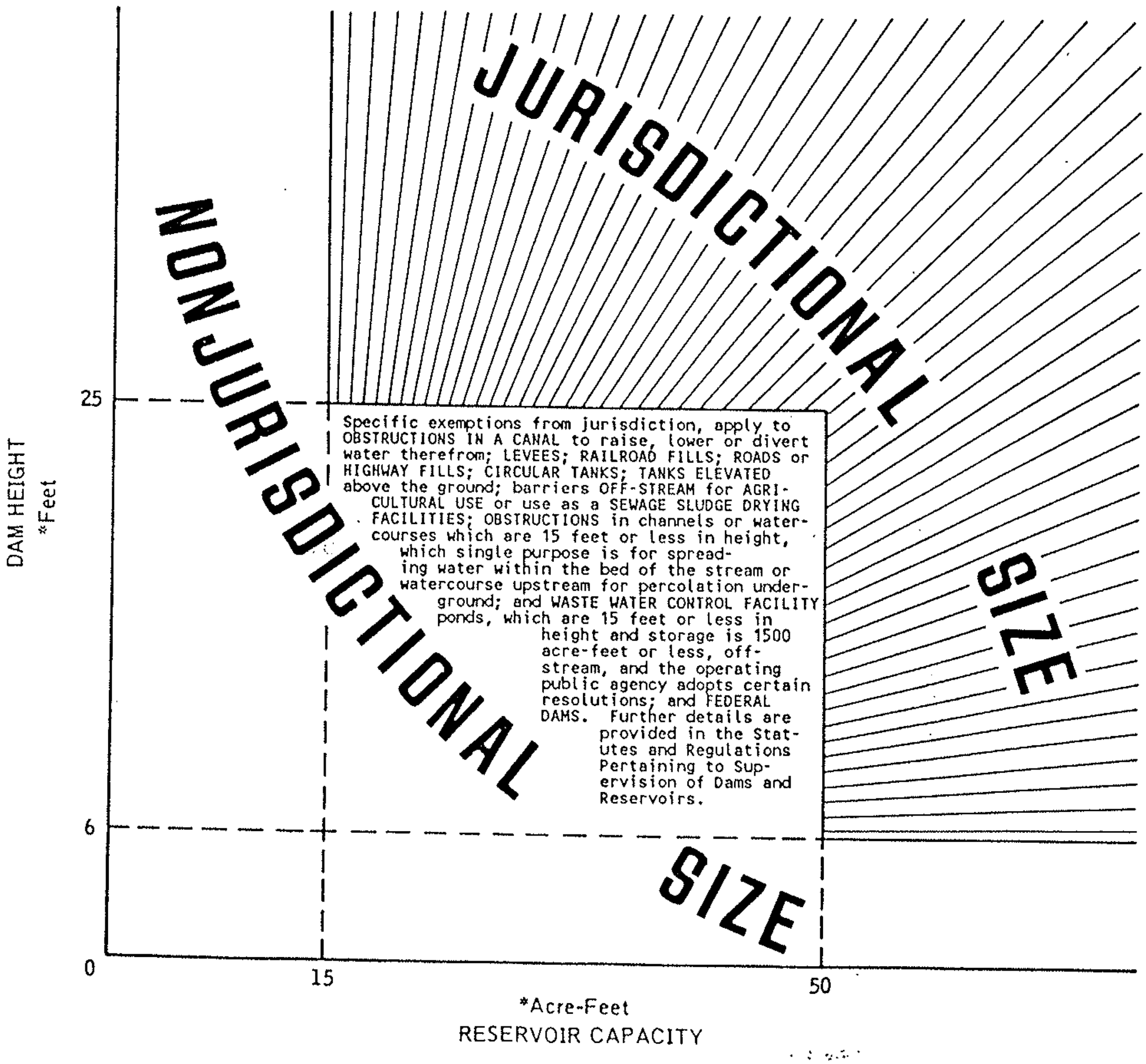
Figure 6. Yuba River Incision During 1986 Flood



(Source: Beak Consultants 1989)

Figure 7. Jurisdictional and Non-Jurisdictional Dam and Reservoir Sizes, Department of Water Resources Division of Dam Safety

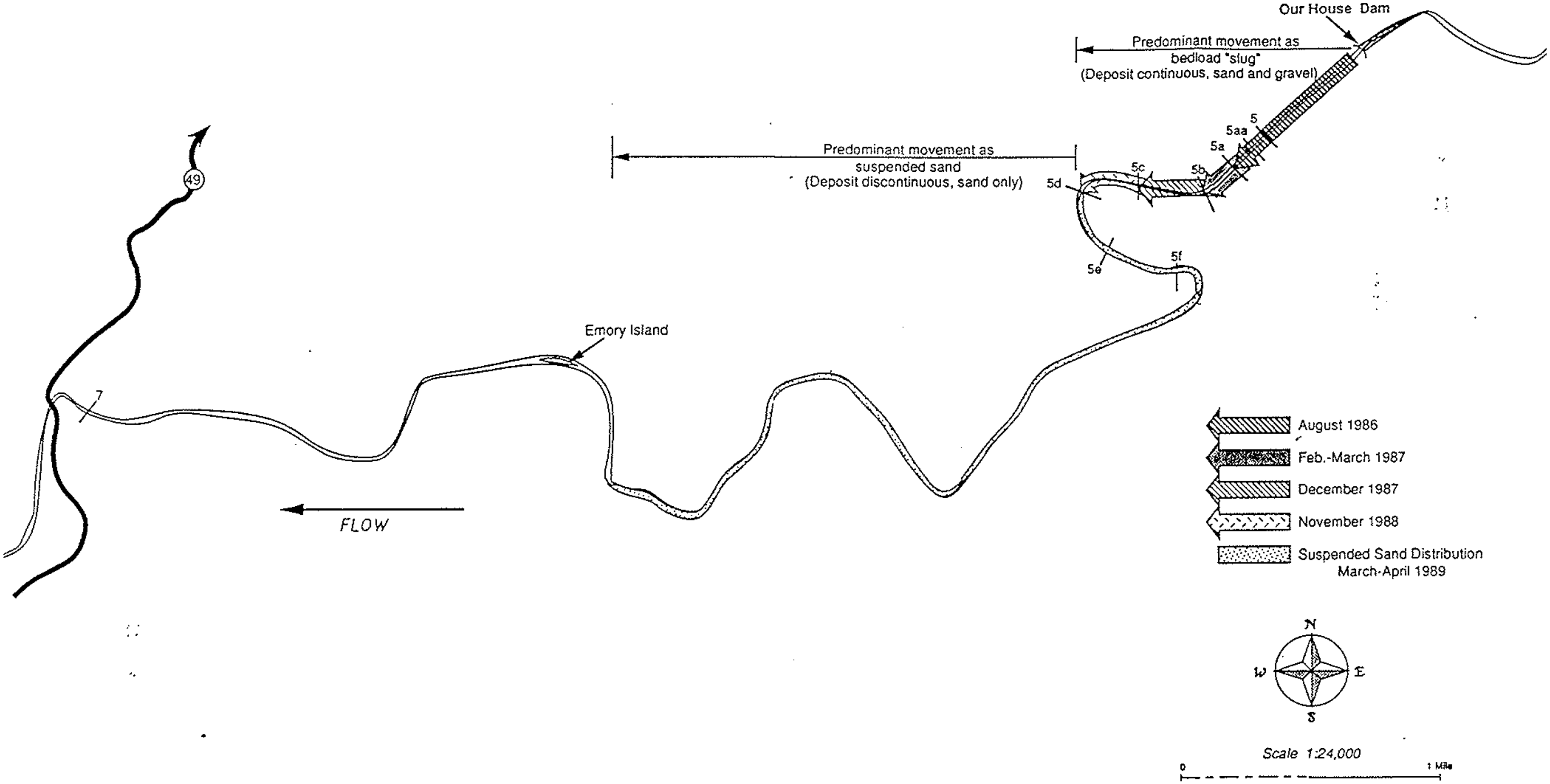
PROVISIONS OF DIVISION 3 OF THE CALIFORNIA WATER CODE AFFECTING JURISDICTION OVER DAMS AND RESERVOIRS



Specific exemptions from jurisdiction, apply to OBSTRUCTIONS IN A CANAL to raise, lower or divert water therefrom; LEVEES; RAILROAD FILLS; ROADS or HIGHWAY FILLS; CIRCULAR TANKS; TANKS ELEVATED above the ground; barriers OFF-STREAM for AGRICULTURAL USE or use as a SEWAGE SLUDGE DRYING FACILITIES; OBSTRUCTIONS in channels or watercourses which are 15 feet or less in height, which single purpose is for spreading water within the bed of the stream or watercourse upstream for percolation underground; and WASTE WATER CONTROL FACILITY ponds, which are 15 feet or less in height and storage is 1500 acre-feet or less, off-stream, and the operating public agency adopts certain resolutions; and FEDERAL DAMS. Further details are provided in the Statutes and Regulations Pertaining to Supervision of Dams and Reservoirs.

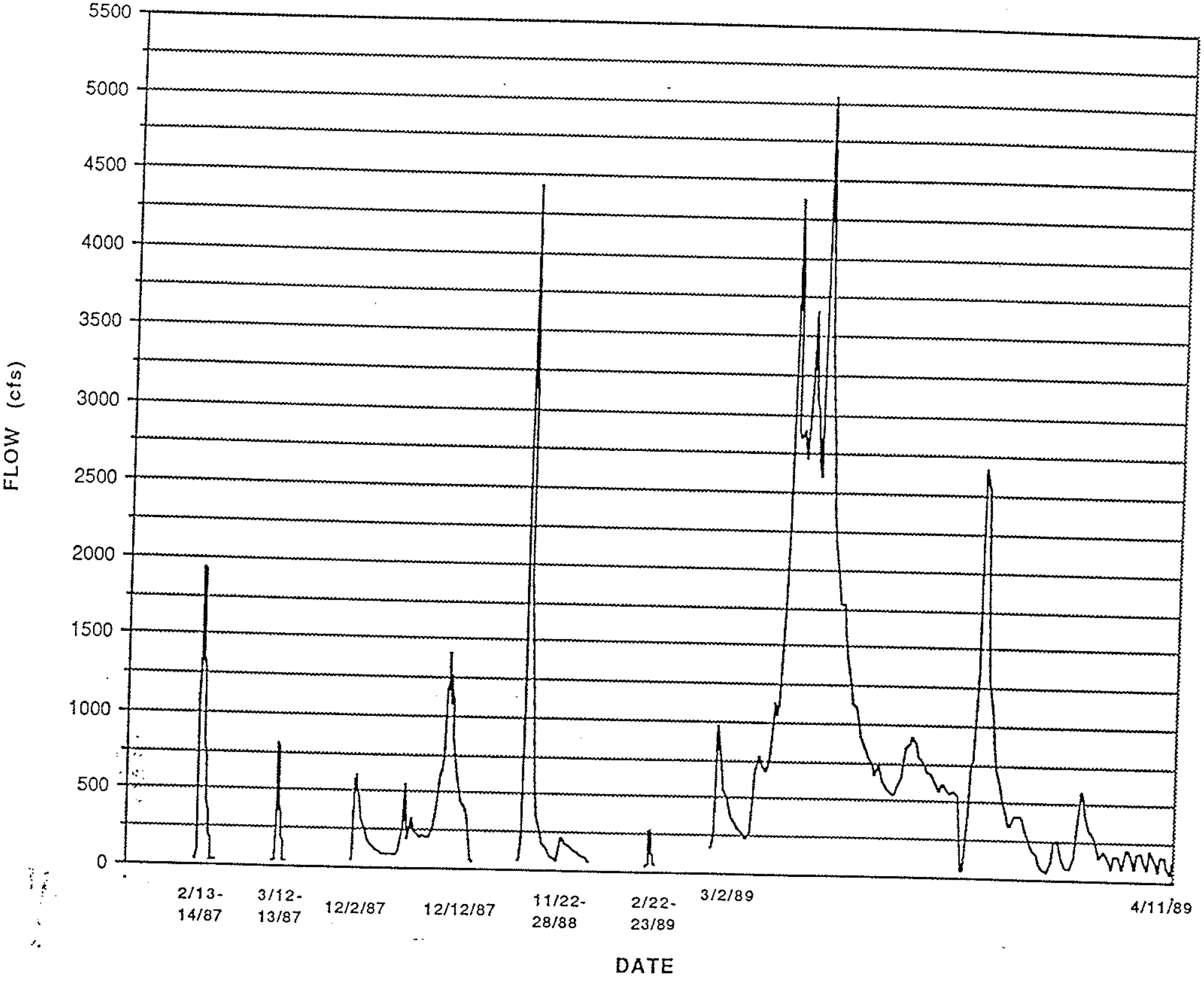
(Source: DWR 1988)

Figure 8. Sediment Movement after Middle Yuba River High Flow Events



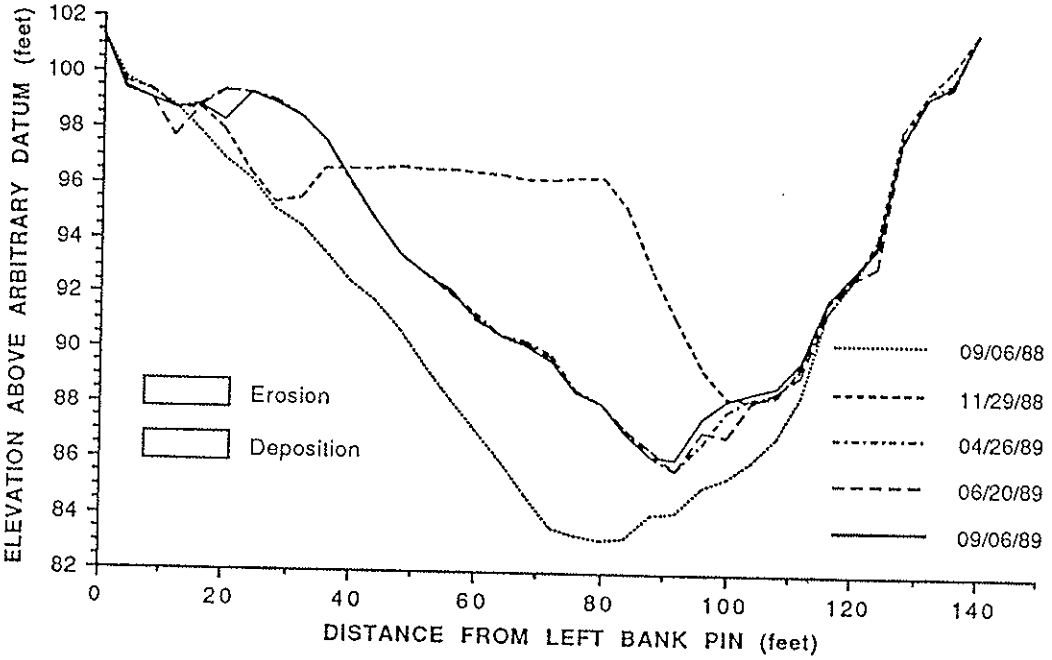
(Source: EBASCO Environmental 1989)

Figure 9. Six Storm Hydrographs for Middle Yuba River below Our House Dam during1987 to 1989



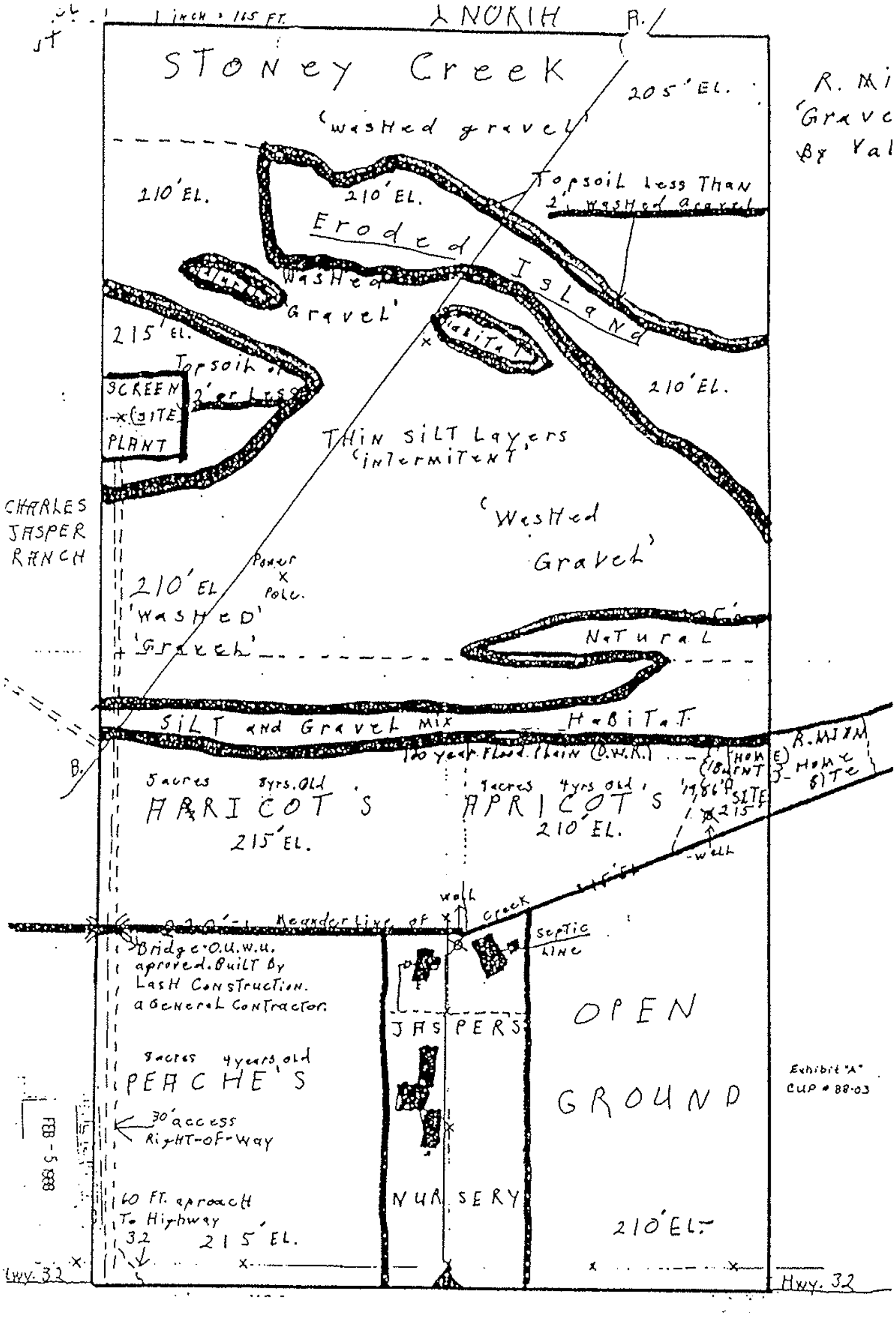
(Source: EBASCO Environmental 1989)

Figure 10. Middle Yuba River Cross-Sectional Changes



(Source: EBASCO Environmental)

Figure 11. Map Submitted with Reclamation Plan to Glenn County



(Source: Swanson & Kondolf 1991)