PROFILE

Hungry Water: Effects of Dams and Gravel Mining on River Channels

G. MATHIAS KONDOLF
Department of Landscape Architecture and Environmental Planning
University of California
Berkeley, California 94720, USA
www.ced.berkeley.edu/~kondolf/

ABSTRACT / Rivers transport sediment from eroding uplands to depositional areas near sea level. If the continuity of sediment transport is interrupted by dams or removal of sediment from the channel by gravel mining, the flow may become sediment-starved (hungry water) and prone to erode the channel bed and banks, producing channel incision (downcutting), coarsening of bed material, and loss of spawning gravels for salmon and trout (as smaller gravels are transported without replacement from upstream). Gravel is artificially added to the River Rhine to prevent further incision and to many other rivers in attempts to restore spawning habitat. It is possible to pass incoming sediment through some small reservoirs, thereby maintaining the continuity of sediment transport through the system. Damming and mining have reduced sediment delivery from rivers to many coastal areas, leading to accelerated beach erosion. Sand and gravel are mined for construction aggregate from river channel and floodplains. In-channel mining commonly causes incision, which may propagate up- and downstream of the mine, undermining bridges, inducing channel instability, and lowering alluvial water tables. Floodplain gravel pits have the potential to become wildlife habitat upon reclamation, but may be captured by the active channel and thereby become instream pits. Management of sand and gravel in rivers must be done on a regional basis, restoring the continuity of sediment transport where possible and encouraging alternatives to river-derived aggregate sources.

As waters flow from high elevation to sea level, their potential energy is converted to other forms as they sculpt the landscape, developing complex channel networks and a variety of associated habitats. Rivers accomplish their geomorphic work using excess energy above that required to simply move water from one point on the landscape to another. In natural channels, the excess energy of rivers is dissipated in many ways: in turbulence at steps in the river profile, in the frictional resistance of cobbles and boulders, vegetation along the bank, in bends, in irregularities of the channel bed and banks, and in sediment transport (Figure 1). The transport of sand- and gravel-sized sediment is particularly important in determining channel form, and a reduction in the supply of these sediments may induce channel changes. The supply of sand and gravel may be the result of many factors, including changes in land use, vegetation, climate, and tectonic activity. This paper is concerned specifically with the response of river channels to a reduction in the supply of these sediments by dams and gravel mining.

Sediment is transported mostly as suspended load: clay, silt, and sand held aloft in the water column by turbulence, in contrast to bedload: sand, gravel, cobbles, and boulders transported by rolling, sliding, and bouncing along the bed (Leopold and others 1964). Bedload ranges from a few percent of total load in lowland rivers to perhaps 15% in mountain rivers (Collins and Dunne 1990), to over 60% in some arid catchments (Schick and Lekach 1993). Although a relatively small part of the total sediment load, the arrangement of bedload sediments constitutes the architecture of sand- and gravel-bed channels. Moreover, gravel and cobbles have tremendous ecological importance, as habitat for benthic macroinvertebrates and as spawning habitat for salmon and trout (Kondolf and Wolman 1993).

The rate of sediment transport typically increases as a power function of flow; that is, a doubling of flow typically produces more than a doubling in sediment transport (Richards 1982), and most sediment transport occurs during floods.

KEY WORDS: Dams; Aquatic habitat; Sediment transport; Erosion; Sedimentation; Gravel mining

Continuity of Sediment Transport in River Systems

Viewed over a long term, runoff erodes the land surface, and the river network carries the erosional products from each basin. The rates of denudation, or lowering of the land by erosion, range widely. The Appalachian Mountains of North America are being denuded about 0.01 mm/yr (Leopold and others 1964), the central Sierra Nevada of California about 0.1

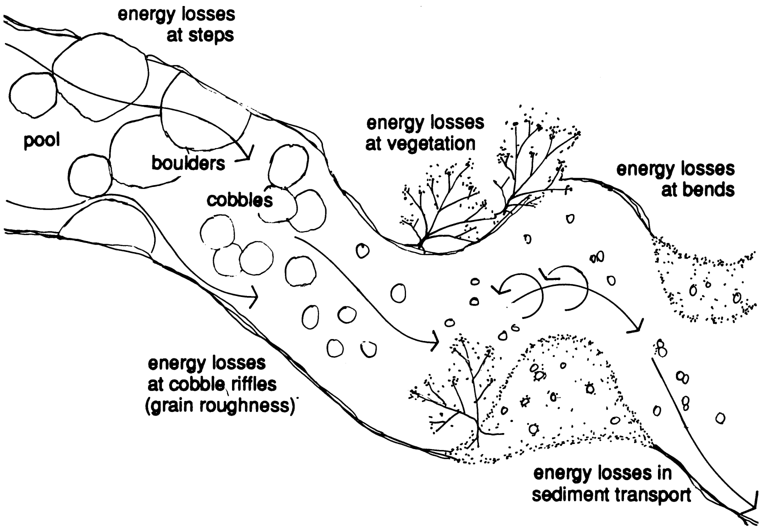

Figure 1. Diagram of energy dissipation in river channels.

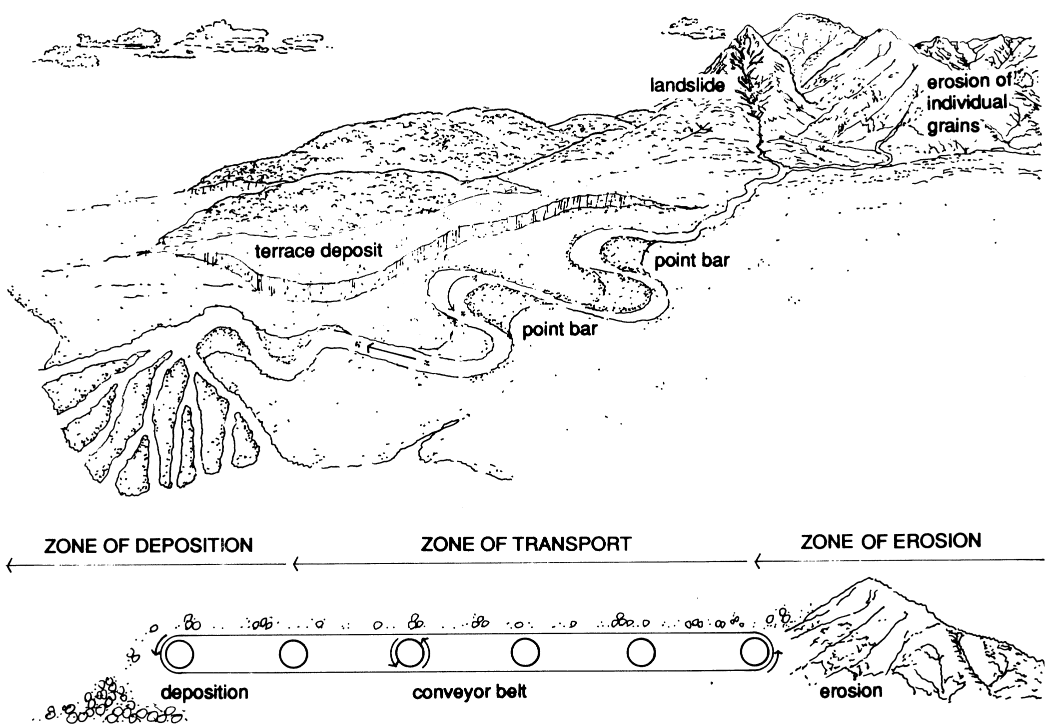

Figure 2. Zones of erosion, transport, and deposition, and the river channel as conveyor belt for sediment. (Reprinted from Kondolf 1994, with kind permission of Elsevier Science-NL.)

mm/yr (Kondolf and Matthews 1993), the Southern Alps of New Zealand about 11 mm/yr (Griffiths and McSaveney 1983), and the southern Central Range of Taiwan over 20 mm/yr (Hwang 1994). The idealized watershed can be divided into three zones: that of erosion or sediment production (steep, rapidly eroding headwaters), transport (through which sediment is moved more or less without net gain or loss), and deposition (Schumm 1977) (Figure 2). The river channel in the transport reach can be viewed as a conveyor belt, which transports the erosional products downstream to the ultimate depositional sites below sea level. The size of sediment typically changes along the length of the river system from gravel, cobbles, and boulders in steep upper reaches to sands and silts in low-gradient downstream reaches, reflecting diminution in size by weathering and abrasion, as well as sorting of sizes by flowing water.

Transport of sediment through the catchment and along the length of the river system is continuous. Increased erosion in the upper reaches of the catchment can affect the river environment many miles downstream (and for years or decades) as the increased sediment loads propagate downstream through the river network. On Redwood Creek in Redwood National Park, California, the world's tallest trees are threatened with bank erosion caused by channel aggradation (building up of sediment in the channel), which in turn was caused by clear-cutting of timber on steep slopes in the upper part of the catchment (Madej and Ozaki 1996, Janda 1978).

Along the river channel conveyor belt, channel forms (such as gravel bars) may appear stable, but the grains of which they are composed may be replaced annually or biannually by new sediment from upstream. Similarly, the sediments that make up the river floodplain (the valley flat adjacent to the channel) are typically mobile on a time scale of decades or centuries. The floodplain acts as a storage reservoir for sediments transported in the channel, alternately storing sediments by deposition and releasing sediment to the channel by bank erosion. For example, the Carmel River, California, is flanked by flat surfaces (terraces) that step up from the river. The lowest terrace is the channel of sand and gravel deposited by the 1911 flood, but the surface now stands about 4 m above the present, incised channel (Kondolf and Curry 1986). By 1960, the terrace had been subdivided for low-density housing, despite the recent origin of the land and the potential for future shifts in channel position.

A river channel and floodplain are dynamic features that constitute a single hydrologic and geomorphic unit characterized by frequent transfers of water and sediment between the two components. The failure to appreciate the integral connection between floodplain and channel underlies many environmental problems in river management today.

Effects of Dams

Dams and diversions are constructed and operated for a wide variety of purposes including residential, commercial, and agricultural water supply; flood and / or debris control; and hydropower production. Regardless of their purpose, all dams trap sediment to some degree and most alter the flood peaks and seasonal distribution of flows, thereby profoundly changing the character and functioning of rivers. By changing flow regime and sediment load, dams can produce adjustments in alluvial channels, the nature of which depends upon the characteristics of the original and altered flow regimes and sediment loads.

Dams disrupt the longitudinal continuity of the river system and interrupt the action of the conveyor belt of sediment transport. Upstream of the dam, all bedload sediment and all or part of the suspended load (depending upon the reservoir capacity relative to inflow) (Brune 1953) is deposited in the quiet water of the reservoir (reducing reservoir capacity) and upstream of the reservoir in reaches influenced by backwater. Downstream, water released from the dam possesses the energy to move sediment, but has little or no sediment load. This clear water released from the dam is often referred to as hungry water, because the excess energy is typically expended on erosion of the channel bed and banks for some years following dam construction, resulting in incision (downcutting of the bed) and coarsening of the bed material until equilibrium is reached and the material cannot be moved by the flows. Reservoirs also may reduce flood peaks downstream, potentially reducing the effects of hungry water, inducing channel shrinking, or allowing fine sediments to accumulate in the bed.

Channel Incision

Incision below dams is most pronounced in rivers with fine-grained bed materials and where impacts on flood peaks are relatively minor (Williams and Wolman 1984). The magnitude of incision depends upon the reservoir operation, channel characteristics, bed material size, and the sequence of flood events following dam closure. For example, the easily eroded sand bed channel of the Colorado River below Davis Dam, Arizona, has incised up to 6 m, despite substantial reductions in peak flows (Williams and Wolman 1984). In contrast, the Mokelumne River below Camanche Dam in California has experienced such a dramatic reduction in flood regime (and consequent reduction in sediment transport capacity) that no incision has been documented and gravels are reported to have become compacted and immobile (FERC 1993).

Reduction in bedload sediment supply can induce a change in channel pattern, as occurred on Stony Creek, a tributary to the Sacramento River 200 km north of San Francisco. Since the closure of Black Butte Dam in 1963, the formerly braided channel has adopted a single-thread meandering pattern, incised, and migrated laterally, eroding enough bedload sediment to compensate for about 20% of the bedload now trapped by Black Butte Dam on an annual average basis (Kondolf and Swanson 1993).

Bed Coarsening and Loss of Spawning Gravels

Channel erosion below dams is frequently accompanied by a change in particle size on the bed, as gravels and finer materials are winnowed from the bed and transported downstream, leaving an armor layer, a coarse lag deposit of large gravel, cobbles, or boulders. Development of an armor layer is an adjustment by the river to changed conditions because the larger particles are less easily mobilized by the hungry water flows below the dam. The armor layer may continue to coarsen until the material is no longer capable of being moved by the reservoir releases or spills, thereby limiting the ultimate depth of incision (Williams and Wolman 1984, Dietrich and others 1989).

The increase in particle size can threaten the success of spawning by salmonids (salmon and trout), which use freshwater gravels to incubate their eggs. The female uses abrupt upward jerks of her tail to excavate a small pit in the gravel bed, in which she deposits her eggs and the male releases his milt. The female then loosens gravels from the bed upstream to cover the eggs and fill the pit. The completed nests (redds) constitute incubation environments with intragravel flow of water past the eggs and relative protection from predation. The size of gravel that can be moved to create a redd depends on the size of the fish, ranging in median diameter from about 15 mm for small trout to about 50 mm for large salmon (Kondolf and Wolman 1993).

Below dams, the bed may coarsen to such an extent that the fish can no longer move the gravel. The Upper Sacramento River, California, was once the site of extensive spawning by chinook salmon (*Oncorhynchus tshawytscha*), but massive extraction of gravel from the riverbed, combined with trapping of bedload sediment behind Shasta Dam upstream and release of hungry water, has resulted in coarsening of the bed such that spawning habitat has been virtually eliminated in the reach (Figure 3) (Parfitt and Buer 1980). The availability of spawning gravels can also be reduced by incision below dams when formerly submerged gravel beds are isolated as terrace or floodplain deposits. Encroaching vegetation can also stabilize banks and further reduce gravel recruitment for redds (Hazel and others 1976).

Figure 3. Keswick Dam and the channel of the Sacramento River downstream. (Photograph by the author, January 1989.)

Gravel Replenishment Below Dams

Gravels were being artificially added to enhance available spawning gravel supply below dams on at least 13 rivers in California as of 1992 (Kondolf and Matthews 1993). The largest of these efforts is on the Upper Sacramento River, where from 1979 to 2000 over US$22 million will have been spent importing gravel (derived mostly from gravel mines on tributaries) into the river channel (Denton 1991) (Figure 4). While these projects can provide short-term habitat, the amount of gravel added is but a small fraction of the bedload deficit below Shasta Dam, and gravels placed in the main river have washed out during high flows, requiring continued addition of more imported gravel (California Department of Water Resources 1995). On the Merced, Tuolumne, and Stanislaus rivers in California, a total of ten sites were excavated and back-filled with smaller gravel to create spawning habitat for chinook salmon from 1990 to 1994. However, the gravel sizes imported were mobile at high flows that could be expected to occur every 1.5–4.0 years, and subsequent channel surveys have demonstrated that imported gravels have washed out (Kondolf and others 1996a,b).

On the border between France and Germany, a series of hydroelectric dams was constructed on the River Rhine (progressing downstream) after 1950, the last of which (the Barrage Iffezheim) was completed in the 1970s. To address the sediment deficit problem downstream of Iffezheim, an annual average of 170,000 tonnes of gravel (the exact amount depending on the

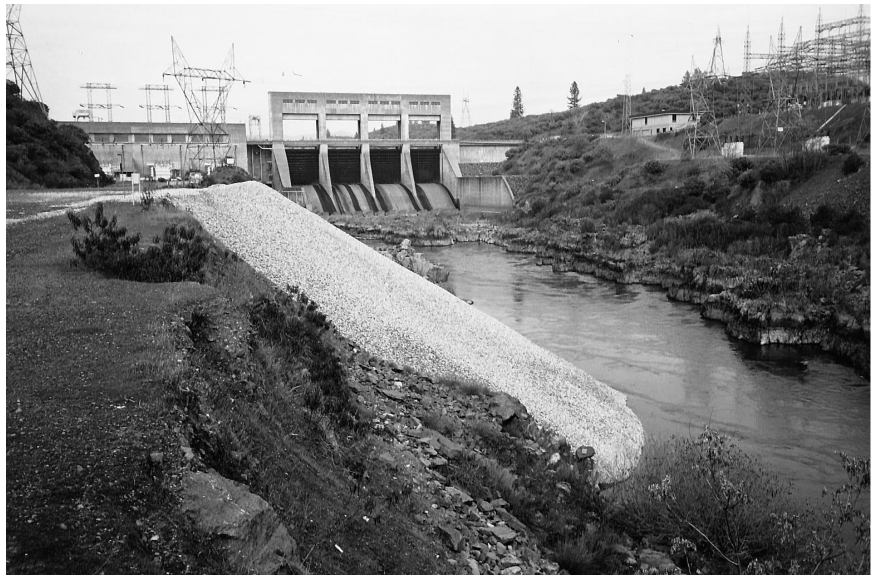

Figure 4. Gravel replenishment to the Sacramento River below Keswick Dam. (Photograph by the author, January 1991.)

magnitude of the year's runoff) are added to the river (Figure 5). This approach has proved successful in preventing further incision of the riverbed downstream (Kuhl 1992). It is worth noting that the quantity of gravel added each year is not equivalent to the unregulated sediment load of the Rhine; the river's capacity to transport sediment has also been reduced because the peak discharges have been reduced by reservoir regulation. The amount of sediment added satisfies the transport capacity of the existing channel, which has been highly altered for navigation and hydroelectric generation.

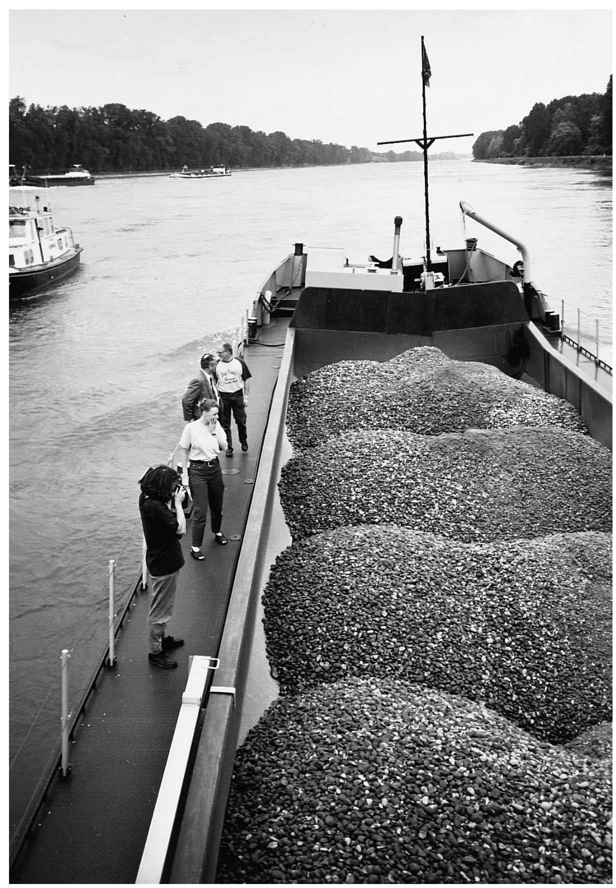

Figure 5. Barge artificially feeding gravel into the River Rhine downstream of the Barrage Iffezheim. (Photograph by author, June 1994.)

Sediment Sluicing and Pass-Through from Reservoirs

The downstream consequences of interrupting the flux of sand and gravel transport would argue for designing systems to pass sediment through reservoirs (and thereby reestablish the continuity of sediment transport). To date, most such efforts have been undertaken to solve problems with reservoir sedimentation, particularly deposits of sediment at tunnel intakes and outlet structures, rather than to solve bedload sediment supply problems downstream. These efforts have been most common in regions with high sediment yields such as Asia (e.g., Sen and Srivastava 1995, Chongshan and others 1995, Hassanzadeh 1995). Small diversion dams (such as those used to divert water in run-of-the-river hydroelectric generating projects) in steep V-shaped canyons have the greatest potential to pass sediment. Because of their small size, these reservoirs (or fore-bays) can easily be drawn down so that the river's gradient and velocity are maintained through the dam

Figure 6. Sand deposited in the bed of the Kern River as a result of sluicing from Democrat Dam in 1986. (Photograph by the author, December 1990.)

at high flow. Large-capacity, low-level outlets are required to pass the incoming flow and sediment load.

If low-level outlets are open at high flow and the reservoir is drawn down, a small reservoir behaves essentially as a reach of river, passing inflowing sediment through the dam outlets. In such a sediment pass-through approach, the sediment is delivered to downstream reaches in essentially the same concentration and seasonal flood flows as prevailed in the predam regime. This approach was employed at the old Aswan Dam on the River Nile and on the Bhatgurk Reservoir on the Yeluard River in India (Stevens 1936). Similarly, on the River Inn in Austria and Germany, floodwaters with high suspended loads are passed through a series of hydropower reservoirs in a channel along the reservoir bottom confined by training walls (Hack 1986, Westrich and others 1992). If topographic conditions are suitable, sediment-laden floodwater may be routed around a reservoir in a diversion tunnel or permitted to pass through the length of the reservoir as a density current vented through a bottom sluice on the dam (Morris 1993). The Nan-Hwa Reservoir in Taiwan was designed with a smaller upstream forebay from which sediment is flushed into a diversion tunnel, allowing only relatively clear water to pass into the main reservoir downstream (Morris 1993).

If sediment is permitted to accumulate in the reservoir and subsequently discharged as a pulse (sediment sluicing), the abrupt increase in sediment load may alter substrate and aquatic habitat conditions downstream of the dam. The most severe effects are likely to occur when sediment accumulated over the flood season is discharged during baseflow (by opening the outlet pipe or sluice gates and permitting the reservoir to draw down sufficiently to resuspend sediment and move bedload), when the river's transporting capacity is inadequate to move the increased load. On the Kern River, the Southern California Edison Company (an electric utility) obtained agency permission to sluice sand from Democrat Dam in 1986, anticipating that the sand would be washed from the channel the subsequent winter. However, several years of drought ensued, and the sand remained within the channel until high flows in 1992 (Figure 6) (Dan Christenson, California Department of Fish and Game, Kernville, personal communication 1992).

On those dams larger than small diversion structures, the sediment accumulated around the outlet is usually silt and clay, which can be deleterious to aquatic habitat and water quality (Bjornn and Reiser 1991). Opening of the low-level outlet on Los Padres Dam on the Carmel River, California, released silt and clay, which resulted in a large fish kill in 1980 (Buel 1980). The dam operator has since been required to use a suction dredge to maintain the outlet (D. Dettman, Monterey Peninsula Water Management District, personal communication 1990). On the Dan River in Danville, Virginia, toxicity testing is required during sluicing of fine sediments from Schoolfield Dam (FERC 1995). Accidental sluices have also occurred during maintenance or repair work, sometimes resulting in substantial cleanup operations for the dam operators (Ramey and Beck 1990, Kondolf 1995).

Less serious effects are likely when the sediment pulse is released during high flows, which will have elevated suspended loads, but which can typically disperse the sediment for some distance downstream. The Jansanpei Reservoir in Taiwan is operated to provide power for the Taiwan Sugar Company, which needs power for processing only from November to April. The reservoir is left empty with open low-level outlets for the first two months of the rainy season (May and June), so sediments accumulated over the months of July–April can be flushed by the first high flows of the season before storing water in the latter part of the rainy season (Hwang 1994).

At present, sediment pass-through is not commonly done in North America, probably because of the limited capacity of many low-level outlets and because of concern that debris may become stuck in the outlets, making them impossible to close later, and making diversions impossible during the rest of the wet season until flows drop sufficiently to fix the outlets. These concerns can probably be addressed with engineering solutions, such as trash racks upstream of the outlet and redundancies in gate structures on the low-level outlet. Large reservoirs cannot be drawn down sufficiently to transport sediment through their length to the outlet works, for such a drawdown would eliminate carryover storage from year to year, an important benefit from large reservoirs.

In most reservoirs in the United States, sediment is simply permitted to accumulate. Active management of sediment in reservoirs has been rare, largely because the long-term costs of reservoir storage lost to sedimentation have not been incorporated into decision-making and planning for reservoirs. Most good reservoir sites are already occupied by reservoirs, and where suitable replacement reservoir sites exist, the current cost of replacement storage (about US\$3/m^3 in California) is considerably higher than original storage costs. Mechanical removal is prohibitively expensive in all but small reservoirs, with costs of \$15–\$50/m^3 cited for the Feather River in California (Kondolf 1995).

Channel Narrowing and Fine Sediment Accumulation Below Dams

While many reservoirs reduce flood peaks, the degree of reduction varies considerably depending upon reservoir size and operation. The larger the reservoir capacity relative to river flow and the greater the flood pool available during a given flood, the greater the reduction in peak floods. Flood control reservoirs typically contain larger floods than reservoirs operated solely for water supply. Downstream of the reservoir, encroachment of riparian vegetation into parts of the active channel may occur in response to a reduction in annual flood scour and sediment deposition (Williams and Wolman 1984). Channel narrowing has been greatest below reservoirs that are large enough to contain the river's largest floods. In some cases, fine sediment delivered to the river channel by tributaries accumulates in spawning gravels because the reservoir-reduced floods are inadequate to flush the riverbed clean.

On the Trinity River, California, construction of Trinity Dam in 1960 reduced the two-year flow from 450 m^3/sec to 9 m^3/sec. As a result of this dramatic change in flood regime, encroachment of vegetation and deposition of sediment has narrowed the channel to 20%–60% of its predam width (Wilcock and others 1996). Accumulation of tributary-derived decomposed granitic sand in the bed of the Trinity River has led to a decline of invertebrate and salmonid spawning habitat (Fredericksen, Kamine and Associates 1980). Experimental, controlled releases were made in 1991, 1992, 1993, 1995, and 1996 to determine the flows required to flush the sand from the gravels (Wilcock and others 1996).

Such flushing flows increasingly have been proposed for reaches downstream of reservoirs to remove fine sediments accumulated on the bed and to scour the bed frequently enough to prevent encroachment of riparian vegetation and narrowing of the active channel (Reiser and others 1989). The objectives of flushing flows have not always been clearly specified, nor have potential conflicts always been recognized. For example, a discharge that mobilizes the channel bed to flush interstitial fine sediment will often produce comparable transport rates of sand and gravel, eliminating the selective transport of sand needed to reduce the fine sediment content in the bed, and resulting in a net loss of gravel from the reach given its lack of supply from upstream (Kondolf and Wilcock 1996).

Coastal Erosion

Beaches serve to dissipate wave action and protect coastal cliffs. Sand may be supplied to beaches from headland erosion, river transport, and offshore sources. If sand supply is reduced through a reduction in sediment delivery from rivers and streams, the beach may become undernourished, shrink, and cliff erosion may be accelerated. This process by which beaches are reduced or maintained can be thought of in terms of a sediment balance between sources of sediment (rivers and headland erosion), the rate of longshore transport along the coast, and sediment sinks (such as loss to deeper water offshore) (Inman 1976). Along the coast of southern California, discrete coastal cells can be identified, each with distinct sediment sources (sediment delivery from river mouths) and sinks (losses to submarine canyons). For example, for the Oceanside littoral cell, the contribution from sediment sources (Santa Margarita, San Luis Rey, and San Dieguito rivers and San Mateo and San Juan creeks) was estimated,

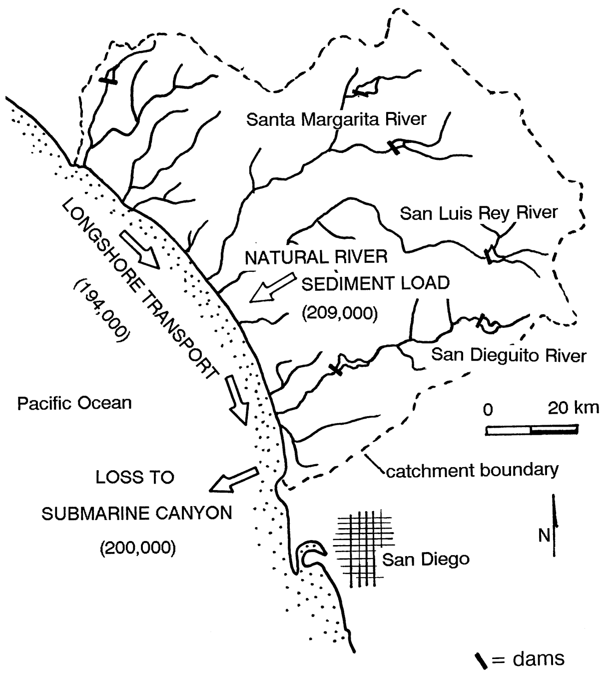

Figure 7. The Oceanside littoral cell, showing estimated sand and gravel supply from rivers, longshore transport, and loss to the La Jolla submarine canyon (in m^3/yr). (Adapted from Inman 1985, used by permission.)

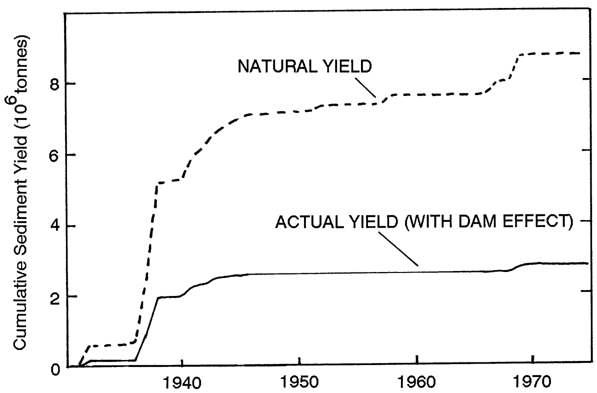

Figure 8. Cumulative reduction in suspended sediment supply from the catchment of the San Luis Rey River due to construction of Henshaw Dam. (Adapted from Brownlie and Taylor 1981.)

under natural conditions, at 209,000 m^3/yr, roughly balancing the longshore transport rate of 194,000 m^3/yr and the loss into the La Jolla submarine canyon of 200,000 m^3/yr (Figure 7) (Inman 1985).

The supply of sediment to beaches from rivers can be reduced by dams because dams trap sediment and because large dams typically reduce the magnitude of floods, which transport the majority of sediment (Jenkins and others 1988). In southern California rivers, most sediment transport occurs during infrequent floods (Brownlie and Taylor 1981), but it is these energetic events that flood control dams are constructed to prevent. On the San Luis Rey River, one of the principal sources of sediment for the Oceanside littoral cell, Henshaw Dam reduced suspended sediment yield by 6 million tonnes (Figure 8), total sand and gravel yield by 2 million tonnes (Brownlie and Taylor 1981).

Ironically, by trapping sediment and reducing peak flows, the flood control dams meant to reduce property damage along rivers contribute to property damage along the coast by eliminating sediment supply to the protective beaches. For the rivers contributing sediment to the Oceanside littoral cell as a whole, sediment from about 40% of the catchment area is now cut off by dams. Because the rate of longshore transport (a function of wave energy striking the coast) is unchanged, the result has been a sediment deficit, loss of beach sand, and accelerated coastal erosion (Inman 1985).

The effects of sediment trapping by dams has been exacerbated in combination with other effects such as channelization and instream sand and gravel mining (discussed below). Although sluicing sediment from reservoirs has been considered in the Los Angeles Basin, passing sediment through urban flood control channels could cause a number of problems, including decreasing channel capacity (Potter 1985). "Beach nourishment" with imported sediment dredged from reservoirs and harbors has been implemented along many beaches in southern California (Inman 1976, Allayaud 1985, Everts 1985). In some cases, sand is transported to critical locations on the coast via truck or slurry pipelines. The high costs of transportation, sorting for the proper size fractions, and cleaning contaminated dredged material, as well as the difficulty in securing a stable supply of material make these options infeasible in some places (Inman 1976).

To integrate considerations of fluvial sediment supply in the maintenance of coastal beaches into the existing legal framework, a system of "sand rights," analogous to water rights, has been proposed (Stone and Kaufman 1985).

Gravel Mining in River Systems

Sand and gravel are used as construction aggregate for roads and highways (base material and asphalt), pipelines (bedding), septic systems (drain rock in leach fields), and concrete (aggregate mix) for highways and buildings. In many areas, aggregate is derived primarily from alluvial deposits, either from pits in river floodplains and terrances, or by in-channel (instream) mining, removing sand and gravel directly from river beds with heavy equipment.

Sand and gravel that have been subject to prolonged transport in water (such as active channel deposits) are particularly desirable sources of aggregate because weak materials are eliminated by abrasion and attrition, leaving durable, rounded, well-sorted gravels (Barksdale 1991). Instream gravels thus require less processing than many other sources, and suitable channel deposits are commonly located near the markets for the product or on transportation routes, reducing transportation costs (which are the largest costs in the industry). Moreover, instream gravels are typically of sufficiently high quality to be classified as ‘‘PCC-grade’’ aggregate, suitable for use in production of Portland Cement concrete (Barksdale 1991).

Effects of Instream Gravel Mining

Instream mining directly alters the channel geometry and bed elevation and may involve extensive clearing, diversion of flow, stockpiling of sediment, and excavation of deep pits (Sandecki 1989). Instream mining may be carried out by excavating trenches or pits in the gravel bed, or by gravel bar skimming (or scalping), removing all the material in a gravel bar above an imaginary line sloping upwards from the summer water's edge. In both cases, the preexisting channel morphology is disrupted and a local sediment deficit is produced, but trenching also leaves a headcut on its upstream end. In addition to the direct alterations of the river environment, instream gravel mining may induce channel incision, bed coarsening, and lateral channel instability (Kondolf 1994).

Channel Incision and Bed Coarsening

By removing sediment from the channel, instream gravel mining disrupts the preexisting balance between sediment supply and transporting capacity, typically inducing incision upstream and downstream of the extraction site. Excavation of pits in the active channel alters the equilibrium profile of the streambed, creating a locally steeper gradient upon entering the pit (Figure 9). This over-steepened nickpoint (with its increased stream power) commonly erodes upstream in a process known as headcutting. Mining-induced incision may propagate upstream for kilometers on the main river (Scott 1973, Stevens and others 1990) and up tributaries (Harvey and Schumm 1987). Gravel pits trap much of the incoming bedload sediment, passing hungry water downstream, which typically erodes the channel bed and banks to regain at least part of its sediment load (Figure 9).

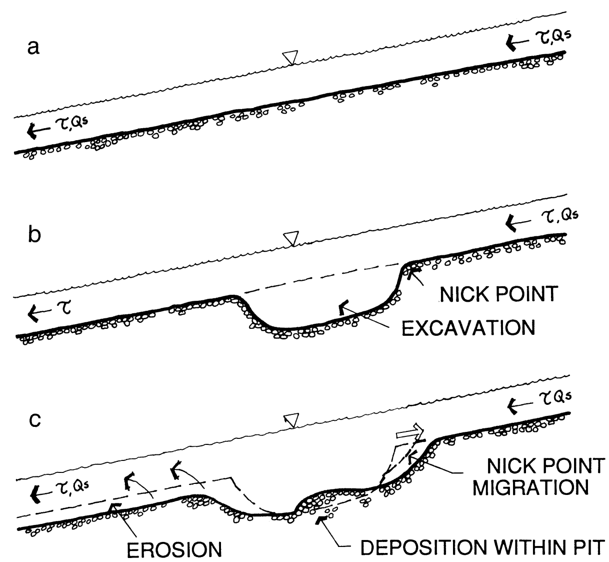

Figure 9. Incision produced by instream gravel mining. **a:** The initial, preextraction condition, in which the river's sediment load (Q_s) and the shear stress (τ) available to transport sediment are continuous through the reach. **b:** The excavation creates a nickpoint on its upstream end and traps sediment, interrupting the transport of sediment through the reach. Downstream, the river still has the capacity to transport sediment (τ) but no sediment load. **c:** The nickpoint migrates upstream, and hungry water erodes the bed downstream, causing incision upstream and downstream. (Reprinted from Kondolf 1994, with kind permission of Elsevier Science-NL.)

A vivid example of mining-induced nickpoint migration appears on a detailed topographic map prepared from analysis of 1992 aerial photographs of Cache Creek, California. The bed had been actively mined up to the miner's property boundary about 1400 m downstream of Capay Bridge, with a 4-m high headwall on the upstream edge of the excavation. After the 1992 winter flows, a nickpoint over 3 m deep extended 700 m upstream from the upstream edge of the pit (Figure 10). After the flows of 1993, the nickpoint had migrated another 260 m upstream of the excavation (not shown), and in the 50-yr flood of 1995, the nickpoint migrated under the Capay Bridge, contributing to the near-failure of the structure (Northwest Hydraulics Consultants 1995).

On the Russian River near Healdsburg, California, instream pit mining in the 1950s and 1960s caused channel incision in excess of 3–6 m over an 11-km length of river (Figure 11). The formerly wide channel of the Russian River is now incised, straighter, prevented from migrating across the valley floor by levees, and thus unable to maintain the diversity of successional

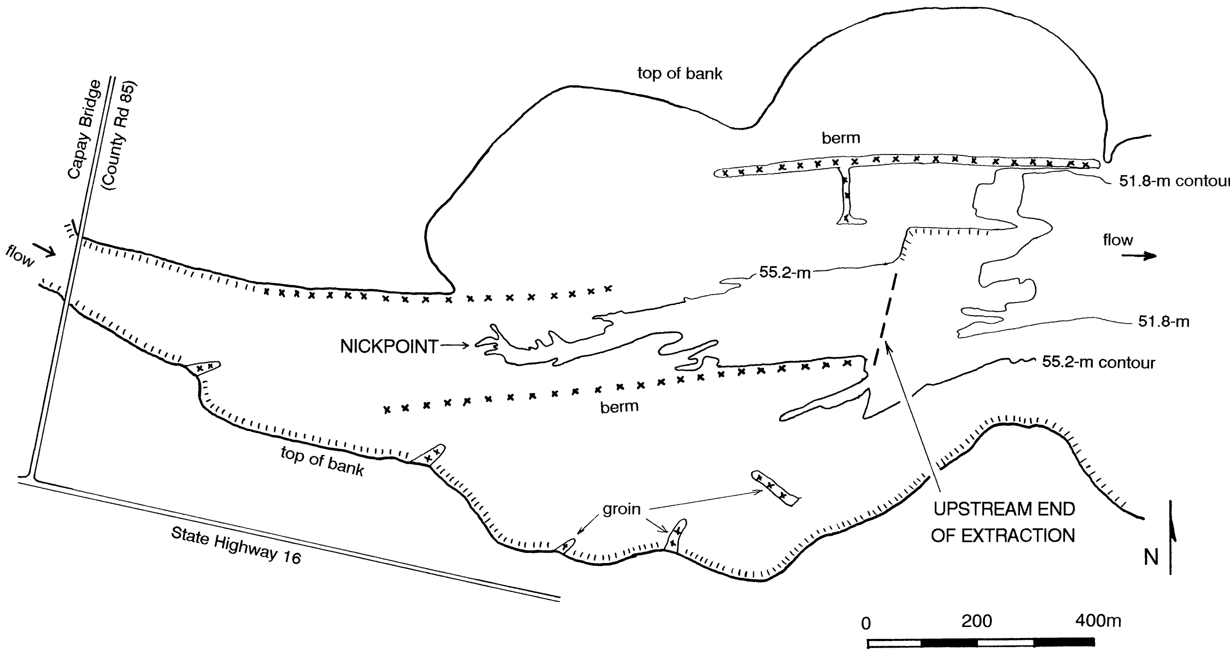

Figure 10. Nickpoint upstream of 4-m-deep gravel pit in the bed of Cache Creek, California, as appearing on a topographic map of Cache Creek prepared from fall 1992 aerial photographs. Original map scale 1:2400, contour interval 0.6 m.

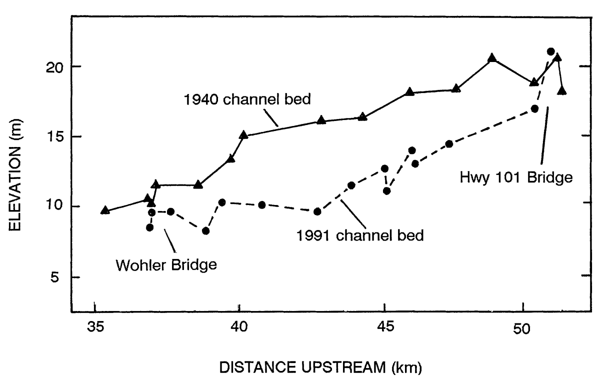

Figure 11. Longitudinal profile of the Russian River, near Healdsburg, California, showing incision from 1940 to 1991. (Redrawn from Florsheim and Goodwin 1993, used by permission.)

stages of vegetation associated with an actively migrating river (Florsheim and Goodwin 1993). With continued extraction, the bed may degrade down to bedrock or older substrates under the recent alluvium (Figure 12). Just as below dams, gravel-bed rivers may become armored, limiting further incision (Dietrich and others 1989), but eliminating salmonid spawning habitat.

In many rivers, gravel mining has been conducted downstream of dams, combining the effects of both impacts to produce an even larger sediment deficit. On the San Luis Rey River downstream of Henshaw Dam, five gravel mining operations within 8 km of the Highway 395 bridge extract a permitted volume of approximately 300,000 m^3/yr, about 50 times greater than the estimated postdam bedload sediment yield (Kondolf and Larson 1995), further exacerbating the coastal sediment deficit.

Incision of the riverbed typically causes the alluvial aquifer to drain to a lower level, resulting in a loss of aquifer storage, as documented along the Russian River (Sonoma County 1992). The Lake County (California) Planning Department (Lake County 1992) estimated that incision from instream mining in small river valleys could reduce alluvial aquifer storage from 1% to 16%, depending on local geology and aquifer geometry.

Undermining of Structures

The direct effects of incision include undermining of bridge piers and other structures, and exposure of buried pipeline crossings and water-supply facilities. Headcutting of over 7 m from an instream gravel mine downstream on the Kaoping River, Taiwan, threatens the Kaoping Bridge, whose downstream margin is now protected with gabions, massive coastal concrete jacks, and lengthened piers (Figure 13).

On the San Luis Rey River, instream gravel mining has not only reduced the supply of sediment to the coast, but mining-induced incision has exposed aqueducts, gas pipelines, and other utilities buried in the

Figure 12. Tributary to the Sacramento River near Redding, California, eroded to bedrock as a result of instream mining. (Photograph by author, January 1989.)

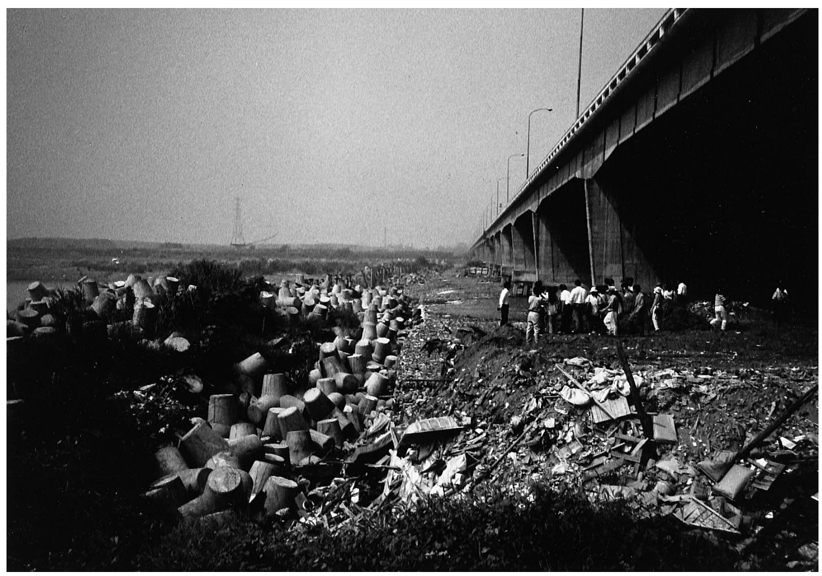

Figure 13. Undercutting and grade control efforts along the downstream side of the Kaoping Bridge over the Kaoping River, Taiwan, to control incision caused by massive gravel mining downstream. (Photograph by the author, October 1995.)

bed and exposed the footings of a major highway bridge (Parsons Brinkeroff Gore & Storrie, Inc. 1994). The Highway 32 bridge over Stony Creek, California, has been undermined as a result of intensive gravel mining directly upstream and downstream of the bridge (Kondolf and Swanson 1993). Municipal water supply intakes have been damaged or made less effective on the Mad (Lehre and others 1993) and Russian (Marcus 1992) rivers in California as the layer of overlying gravel has decreased due to incision.

Channel Instability

Instream mining can cause channel instability through disruption of the existing equilibrium channel form or undercutting of banks caused by incision. Gravel mining in Blackwood Creek, California, caused incision and channel instability upstream and downstream, increasing the stream's sediment yield fourfold (Todd 1989). As a nickpoint migrates upstream, its incision and bank undercutting release additional sediment to downstream reaches, where the channel may aggrade and thereby become unstable (Sear and Archer 1995). Incision in the mainstem Russian River propagated up its tributary Dry Creek, resulting in undercutting of banks, channel widening (from 10 to 400 m in places), and destabilization, increasing delivery of sand and gravel to the mainstem Russian River (Harvey and Schumm 1987).

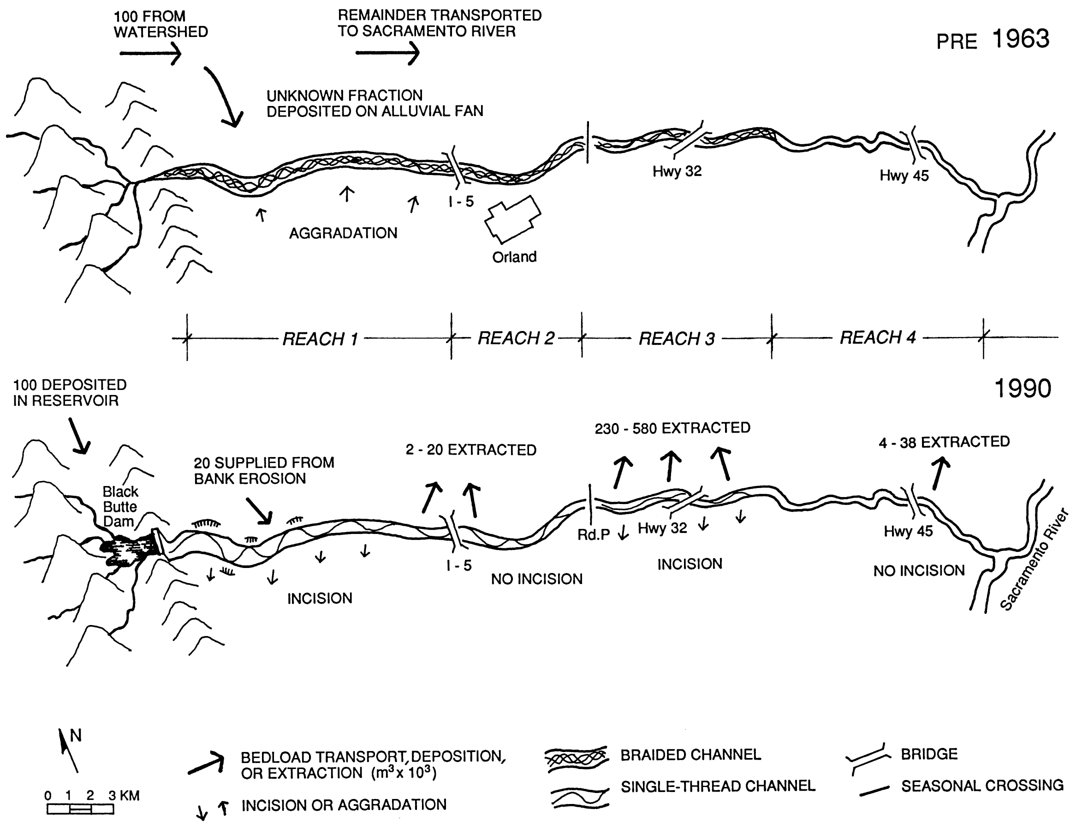

Figure 14. Sediment budget for Stony Creek, California. (Reprinted from Kondolf and Swanson 1993, used by permission of Spring-Verlag, New York.)

A more subtle but potentially significant effect is the increased mobility of the gravel bed if the pavement (the active coarse surface layer) (Parker and Klingeman 1982) is disrupted by mining. Similarly, removal of gravel bars by instream mining can eliminate the hydraulic control for the reach upstream, inducing scour of upstream riffles and thus washout of incubating salmon embryos (Pauley and others 1989).

Secondary Effects of Instream Mining

Among the secondary effects of instream mining are reduced loading of coarse woody debris in the channel, which is important as cover for fish (Bisson and others 1987). Extraction (even bar skimming at low extraction rates) typically results in a wider, shallower streambed, leading to increased water temperatures, modification of pool-riffle distribution, alteration of intergravel flow paths, and thus degradation of salmonid habitat.

Resolving the Effects of Instream Mining from Other Influences

In many rivers, several factors potentially causing incision in the channel may be operating simultaneously, such as sediment trapping by dams, reduced channel migration by bank protection, reduced overbank flooding from levees, and instream mining. However, in many rivers the rate of aggregate extraction is an order of magnitude greater than the rate of sediment supply from the drainage basin, providing strong evidence for the role of extraction in causing channel change. On Stony Creek, the incision produced by Black Butte Reservoir could be clearly distinguished from the effects of instream mining at the Highway 32 bridge by virtue of the distinct temporal and spatial patterns of incision. The dam-induced incision was pronounced downstream of the reservoir soon after its construction in 1963. By contrast, the instream mining (at rates exceeding the predam sediment supply by 200%–600%, and exceeding the postdam sediment supply by 1000%–3000%) produced incision of up to 7 m centered in the mining reach near the Highway 32 bridge, after intensification of gravel mining in the 1970s (Kondolf and Swanson 1993) (Figure 14).

Management of Instream Gravel Mining

Instream mining has long been prohibited in the United Kingdom, Germany, France, the Netherlands, and Switzerland, and it is being reduced or prohibited in many rivers where impacts are apparent in Italy, Portugal, and New Zealand. In the United States and Canada, instream mining continues in many rivers, despite increasing public opposition and recognition of environmental effects by regulatory agencies. Instream mines continue to operate illegally in many places, such as the United States (Los Angeles Times 1992) and Taiwan.

Strategies used to manage instream mining range widely, and in many jurisdictions there is no effective management. One strategy is to define a redline, a minimum elevation for the thalweg (the deepest point in a channel cross section) along the river, and to permit mining so long as the bed does not incise below this line (as determined by annual surveys of river topography). The redline approach addresses a problem common to many permits in California, which have specified that extraction is permitted ''*x* feet below the channel bed'' or only down to the thalweg, without stating these limits in terms of actual elevations above a permanent datum. Thus the extraction limits have migrated vertically downward as the channel incises.

Another approach is to estimate the annual bedload sediment supply from upstream (the replenishment rate) and to limit annual extraction to that value or some fraction thereof, considered the ''safe yield.'' The replenishment rate approach has the virtue of scaling extraction to the river load in a general way, but bedload transport can be notoriously variable from year to year. Thus, this approach is probably better if permitted extraction rates are based on new deposition that year rather than on long-term average bedload yields. More fundamentally, however, the notion that one can extract at the replenishment rate without affecting the channel ignores the continuity of sediment transport through the river system. The mined reach is the ''upstream'' sediment source for downstream reaches, so mining at the replenishment rate could be expected to produce hungry water conditions downstream. Habitat managers in Washington state have sought to limit extraction to 50% of the transport rate as a first-cut estimate of safe yield to minimize effects upon salmon spawning habitat (Bates 1987).

Current approaches to managing instream mining are based on empirical studies. While a theoretical approach to predicting the effects of different levels of gravel mining on rivers would be desirable, the inherent complexity of sediment transport and channel change makes firm, specific predictions impossible at present. Sediment transport models can provide an indication of potential channel incision and aggradation, but all such models are simplifications of a complex reality, and the utility of existing models is limited by unreliable formulation of sediment rating curves, variations in hydraulic roughness, and inadequate understanding of the mechanics of bed coarsening and bank erosion (NRC 1983).

In 1995, the US Department of Transportation issued a notice to state transportation agencies indicating that federal funds will no longer be available to repair bridges damaged by gravel mining, a move that may motivate more vigorous enforcement of regulations governing gravel mining in rivers by states.

Floodplain Pit Mining

Floodplain pit mining transforms riparian woodland or agricultural land into open pits, which typically intersect the water table at least seasonally (Figure 15). Floodplain pit mining has effectively transformed large areas of floodplain into open-water ponds, whose water level commonly tracks that of the main river closely, and which are commonly separated from the active channel by only a narrow strip of unmined land. Because the pits are in close hydrologic continuity with the alluvial water table, concerns are often raised that contamination of the pits may lead to contamination of the alluvial aquifer. Many existing pits are steep-sided (to maximize gravel yield per unit area) and offer relatively limited wetlands habitat, but with improved pit design (e.g., gently sloping banks, irregular shorelines), greater wildlife benefits are possible upon reclamation (Andrews and Kinsman 1990, Giles 1992).

In many cases, floodplain pits have captured the channel during floods, in effect converting formerly off-channel mines to in-channel mines. Pit capture occurs when the strip of land separating the pit from the channel is breached by lateral channel erosion or by overflowing floodwaters. In general, pit capture is most likely when flowing through the pit offers the river a shorter course than the currently active channel.

When pit capture occurs, the formerly off-channel pit is converted into an in-channel pit, and the effects of instream mining can be expected, notably propagation of incision up- and downstream of the pit. Channel capture by an off-channel pit on the alluvial fan of Tujunga Wash near Los Angeles created a nickpoint that migrated upstream, undermining highway bridges (Scott 1973). The Yakima River, Washington, was captured by two floodplain pits in 1971, and began undercutting the highway for whose construction the pits had been originally excavated (Dunne and Leopold 1978). High flows on the Clackamas River, Oregon, in 1996 resulted in capture of an off-channel pit and resulted in 2 m of incision documented about 1 km upstream

Figure 15. Floodplain pit along Cottonwood Creek near Redding, California. (Photograph by author, January 1989.)

Figure 16. Incision of Clackamas River approximately one mile upstream of captured gravel pit near Barton, Oregon. The three men on the right are standing on the bed of a side channel that formerly joined the mainstem at grade, but is now elevated about 2 m above the current river bed, after upstream migration of a nickpoint from the gravel pit. View upstream. (Photograph by author, April 1996.)

(Figure 16) and caused undermining of a building at the gravel mine site (Figure 17).

Off-channel gravel pits have been used successfully as spawning and rearing habitat for salmon and trout in Idaho (Richards and others 1992) and on the Olympic Peninsula of Washington (Partee and Samuelson 1993). In warmer climates, however, these off-channel pits are likely to heat up in the summer and provide habitat for warm-water fish that prey on juvenile salmonids. During floods, these pits may serve as a source of warm-water fish to the main channel, and juvenile salmon can become stranded in the pits. The Merced River, California, flows through at least 15 gravel pits, of which seven were excavated in the active channel, and eight were excavated on the floodplain and subsequently captured the channel (Vick 1995). Juvenile salmon migrating towards the ocean become disoriented in the quiet water of these pits and suffer high losses to predation by largemouth and smallmouth bass (*Micropterus salmoides* and *M. dolomieui*). On the nearby Tuolumne River, a 1987 study by the California Department of Fish and Game estimated that juvenile chinook salmon migrating oceanward suffered 70% losses to predation (mostly in gravel pits) in the three days required to traverse an 80-km reach from LaGrange Dam to the San Joaquin River (EA 1992). To reduce this predation problem, funding has been allocated to repair breached levees at one gravel pit on the Merced River at a cost of

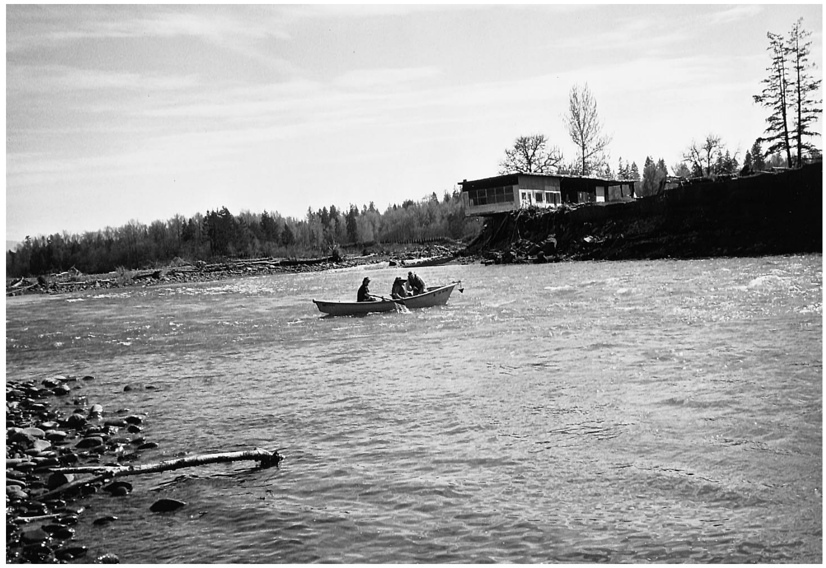

Figure 17. Building undercut by bank erosion as the Clackamas River flows through a captured gravel pit near Barton, Oregon. (Photograph by the author, April 1996.)

US$361,000 (Kondolf and others 1996a), and refilling of two pits on the Tuolumne River has been proposed at a cost of $5.3 million (McBain and Trush 1996).

Aggregate Supply, Quality, and Uses

Aggregates can be obtained from a wide variety of sources (besides fluvial deposits), such as dry terrace mines, quarries (from which rock must be crushed, washed, and sorted), dredger tailings, reservoir deltas, and recycling concrete rubble. These alternative sources usually require more processing and often require longer transportation. Although their production costs are commonly higher, these alternative sources avoid many impacts of riverine extraction and may provide other benefits, such as partially restoring reservoir capacity lost to sedimentation and providing opportunities for ecological restoration of sterile dredger tailings.

In California, most aggregate that has been produced to date has been PCC-grade aggregate from instream deposits or recent channel deposits in floodplains. These deposits were viewed as virtually infinite in supply, and these high-grade aggregates have been used in applications (such as road subbase) for which other, more abundant aggregates (e.g., crushed rock from upland quarries) would be acceptable. Given that demand for aggregate commonly exceeds the supply of sand and gravel from the catchment by an order of magnitude or more, public policy ought to encourage reservation of the most valuable aggregate resources for the highest end uses. PCC-grade instream gravels should be used, to the extent possible, only in applications requiring such high-quality aggregate. Upland quarry and terrace pit sources of lower-grade aggregate should be identified, and alternative sources such as mining gold dredger tailings or reservoir accumulations, should be evaluated. Wherever possible, concrete rubble should be recycled to produce aggregate for many applications.

Reservoir sediments are a largely unexploited source of building materials in the United States. In general, reservoir deposits will be attractive sources of aggregates to the extent that they are sorted by size. The depositional pattern within a reservoir depends on reservoir size and configuration and the reservoir stage during floods. Small diversion dams may have a low trap efficiency for suspended sediments and trap primarily sand and gravel, while larger reservoirs will have mostly finer-grained sand, silt, and clay (deposited from suspension) throughout most of the reservoir, with coarse sediment typically concentrated in deltas at the upstream end of the reservoir. These coarse deposits will extend farther if the reservoir is drawn down to a low level when the sediment-laden water enters. In many reservoirs, sand and gravel occur at the upstream end, silts and clays at the downstream end, and a mixed zone of interbedded coarse and fine sediments in the middle.

Sand and gravel are mined commercially from some debris basins in the Los Angeles Basin and from Rollins Reservoir on the Bear River in California. In Taiwan, most reservoir sediments are fine-grained (owing to the caliber of the source rocks), but where coarser sediments are deposited, they are virtually all mined for construction aggregate (J. S. Hwang, Taiwan Provincial Water Conservancy Bureau, Taichung City, personal communication 1996). In Israel, the 2.2-km-long Shikma Reservoir is mined in its upper 600 m to produce sand and gravel for construction aggregate, and in its lower 1 km to produce clay for use in cement, bricks, clay seals for sewage treatment ponds, and pottery (Laronne 1995, Taig 1996). The zone of mixed sediments in the mid-section of the reservoir is left unexcavated and vegetated so it permits only fine-grained washload to pass downstream into the lower reservoir, thereby ensuring continued deposition of sand and gravel in the upstream portion of the reservoir and silt and clay in the downstream portion. The extraction itself restores some of the reservoir capacity lost to sedimentation. Similarly, on Nahal Besor, Israel, the off-channel Lower Rehovot Reservoir was deliberately created (to provide needed reservoir storage) by gravel mining. Water is diverted into the reservoir through a spillway at high flows, as controlled by a weir across the channel (Cohen 1996).

Extraction of reservoir sediments partially mitigates losses in reservoir capacity from sedimentation. Because of the high costs and practical problems with construction of replacement reservoir storage and/or mechanical removal of sediment, restoration of reservoir capacity may be seen as one of the chief benefits from mining aggregate and industrial clays from reservoirs. If these benefits are recognized, mining reservoir deposits may become more economically attractive in the future, especially if the environmental costs of instream and floodplain mining become better recognized and reflected in the prices of those aggregates. In the United States, construction of reservoirs was often justified partially by anticipated recreational benefits, and thus reservoir margins are commonly designated as recreation areas, posing a potential conflict with an industrial use such as gravel mining. Furthermore, wetlands may form in reservoir delta deposits, posing potential conflicts with regulations protecting wetlands.

Conclusions

Comprehensive management of gravel and sand in river systems should be based on a recognition of the natural flow of sediment through the drainage network and the nature of impacts (to ecological resources and to infrastructure) likely to occur when the continuity of sediment is disrupted. A sediment budget should be developed for present and historical conditions as a fundamental basis for evaluation of these impacts, many of which are cumulative in nature.

The cost of sediment-related impacts of existing and proposed water development projects and aggregate mines must be realistically assessed and included in economic evaluations of these projects. The (very real) costs of impacts such as bridge undermining, loss of spawning gravels, and loss of beach sand are now externalized, borne by other sectors of society rather than the generators of the impacts. The notion of sediment rights (analogous to water rights) should be explored as a framework within which to assess reservoir operations and aggregate mining for these impacts.

Sediment pass-through should be undertaken in reservoirs (where feasible) to mimic the natural flux of sediment through the river system. Pass-through should be done only during high flows when the sediment is likely to continue dispersing downstream from the reservoir. The cost of installing larger low-level outlets (where necessary) on existing dams will generally be less than costs of mechanical removal of sediments over subsequent decades. In larger reservoirs where sediment cannot be passed through a drawn-down reservoir, alternative means of transporting the gravel and sand fractions around (or through) reservoirs using tunnels, pipes, or barges should be explored.

Flushing flows should be evaluated not only in light of potential benefits of flushing fine sediments from mobilized gravels, but also the potential loss of gravel from the reach due to downstream transport.

The regional context of aggregate resources, market demand, and the environmental impacts of various alternatives must be understood before any site-specific proposal for aggregate extraction can be sensibly reviewed. In general, effects of aggregate mining should be evaluated on a river basin scale, so that the cumulative effects of extraction on the aquatic and riparian resources can be recognized. Evaluation of aggregate supply and demand should be undertaken on the basis of production–consumption regions, encompassing the market for aggregate and all potential sources of aggregate within an economical transport distance.

The finite nature of high-quality alluvial gravel resources must recognized, and high-quality PCC-grade aggregates should be reserved only for the uses demanding this quality material (such as concrete). Alternative sources should be used in less demanding applications (such as road subbase). The environmental costs of instream mining should be incorporated into the price of the product so that alternative sources that require more processing but have less environmental impact become more attractive.

Instream mining should not be permitted in rivers downstream of dams by virtue of the lack of supply from upstream or in rivers with important salmon spawning (unless it can be shown that the extraction will not degrade habitat).

Acknowledgments

The concepts presented in this paper have drawn upon research over a decade and interesting discussions with many colleagues, including Ken Bates, Koll Buer, Brian Collins, Cathy Crossett, Peter Geldner, Peter Goodwin, Murray Hicks, Jing-San Hwang, Steve Jones, Pete Klingeman, John Laronne, Han-Bin Liang, Bob MacArthur, Graham Matthews, Scott McBain, Gregg Morris, Mike Sandecki, Mitchell Swanson, Jen Vick, Ed Wallace, Peter Wilcock, and John Williams. This paper has benefitted from critical comments from Mary Ann Madej, Graham Matthews, and an anonymous reviewer. The research upon which this paper is based was partially supported by the University of California Water Resources Center (UC Davis), as part of Water Resources Center project UCAL-WRC-W-748, administered by the Center for Environmental Design Research, and by a grant from the Beatrix Farrand Fund of the Department of Landscape Architecture, both at the University of California, Berkeley.

Literature Cited

Allayaud, W. K. 1985. Innovations in non-structural solutions to preventing coastal damage. Pages 260–290 *in* J. McGrath (ed.), California's battered coast, proceedings from a conference on coastal erosion. California Coastal Commission.

Andrews, J., and D. Kinsman. 1990. Gravel pit restoration for wildlife: a practical manual. The Royal Society for Protection of Birds, Sandy, Bedfordshire.

Barksdale, R. D. 1991. The aggregate handbook. National Stone Association, Washington, DC.

Bates, K. 1987. Fisheries perspectives on gravel removal from river channels. Pages 292–298 *in* Realistic approaches to better floodplain management. Proceedings of the eleventh annual conference of the Association of State Floodplain Managers, Seattle, June 1987. Natural Hazards Research and Applications Information Center, Special Publication No. 18.

Bisson, P. A. and eight coauthors. 1987. Large woody debris in forested streams in the Pacific Northwest: Past present, and future. Pages 143–190 *in* E. O. Salo and T. Cundy (eds.), Proceedings of an interdisciplinary symposium on streamside management: Forestry and fishery interactions. University of Washington Press, Seattle.

Bjornn, T. L., and D. W. Reiser. 1991. Habitat requirements of salmonids in streams. Pages 83–138 *in* Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication 19.

Brownlie, W. R., and B. D. Taylor. 1981. Sediment management for southern California mountains, coastal plain, and shoreline. Part C. Coastal sediment delivery by major rivers in southern California. Report. 17-C, Environmental Quality Lab, California Institute of Technology, Pasadena.

Brune, G. M. 1953. The trap efficiency of reservoirs. *Transactions of the American Geophysical Union* 34:407–418.

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

California Department of Water Resources. 1995. Sacramento River gravel restoration phase II study: A plan for continued spawning gravel replenishment between Keswick Dam and clear Creek. Technical Information Record TIR ND-95-1. California Department of Water Resources, Northern District, Red Bluff, California.

Chongshan, Z., W. Jianguo, and L. Quigmei. 1995. Experiment study of approach for sediment removed from reservoirs. Pages 149–154 *in* Proceedings of sixth international symposium on river sedimentation, New Delhi, India.

Cohen, M. 1996. Structures and sills in river channels. Pages 42–44 *in* J. B. Laronne (ed.), Reservoirs as a source of water for the Negev conference proceedings. Ben-Gurion University, Be'er Sheva, Israel (in Hebrew).

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

Denton, D. N. 1991. Sacramento River gravel restoration progress report. Unpublished report. California Department of Water Resources, Red Bluff, California, January 1991.

Dietrich, W. E., J. W. Kirchner, H. Ikeda, and F. Iseya. 1989. Sediment supply and development of coarse surface layer in gravel bedded rivers. *Nature* 340:215–217.

Dunne, T., and L. B. Leopold. 1978. Water in environmental planning. W. H. Freeman & Sons, San Francisco.

EA (EA Engineering, Science, and Technology). 1992. Don Pedro Project fisheries studies report (FERC Article 39, Project No. 2299). Report to Turlock Irrigation District and Merced Irrigation District.

Everts, C. H. 1985. Effects of small protective devices on beaches. Pages 127–138 *in* J. McGrath (ed.), California's battered coast, proceedings from a conference on coastal erosion. California Coastal Commission.

FERC (Federal Energy Regulatory Commission). 1993. Final environmental impact statement, propose modifications to the Lower Mokelumne River Project, California, FERC Project No. 2916-004. Washington, DC.

FERC (Federal Energy Regulatory Commission). 1995. Order amending and approving sediment flushing plan, STS Hydropower Limited and Dan River Incorporated, FERC Project No. 2411-012. Washington, DC.

Florsheim, J., and P. Goodwin. 1993. Geomorphic and hydrologic conditions in the Russian River, California: Historic trends and existing conditions. Discussion document, prepared for California State Coastal Conservancy, Oakland.

Fredericksen, Kamine, and Associates. 1980. Proposed Trinity River Basin fish and wildlife management program. Unpublished report to US Water and Power Resources Service (now the US Bureau of Reclamation).

Giles, N. 1992. Wildlife after gravel: Twenty years of practical research by The Game Conservancy and ARC. The Game Conservancy, Fordingbridge, Hampshire.

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

Hack, H. P. 1986. Design and calculation of reservoirs of run of river stations incorporating sedimentation. Pages 107–

112 *in* W. Bechteler (ed.), Transport of suspended solids in open channels, proceedings of Euromech 192. Munich, Germany. June 11–15, 1985.

Harvey, M. D., and S. A. Schumm. 1987. Response of Dry Creek, California, to land use change, gravel mining and dam closure. Pages 451–460 *in* Erosion and sedimentation in the Pacific Rim, proceedings of the Corvallis symposium, August 1987. International Association of Hydrological Sciences Publication 165.

Hassanzadeh, Y. 1995. The removal of reservoir sediment. *Water International* 20:151–154.

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 Department of Interior, Fish and Wildlife Service.

Hwang, J. S. 1994. A study of the sustainable water resources system in Taiwan considering the problems of reservoir desilting. Taiwan Provincial Water Conservancy Bureau, Taichung City, Taiwan.

Inman, D. L. 1976. Man's impact on the California coastal zone. Summary report to California Department of Navigation and Ocean Development, Sacramento.

Inman, D. L. 1985. Budget of sand in southern California; river discharge vs. cliff erosion. Pages 10–15 *in* J. McGrath (ed.), California's battered coast, proceedings from a conference on coastal erosion. California Coastal Commission.

Janda, R. J. 1978. Summary of watershed conditions in the vicinity of Redwood National Park. US Geological Survey Open File Report 78-25, Menlo Park, California.

Jenkins, S. A., D. L. Inman, and D. W. Skelly. 1988. Impact of dam building on the California coastal zone. *California Waterfront Age* September.

Kondolf, G. M. 1994. Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning* 28:225–243.

Kondolf, G. M. 1995. Managing bedload sediments in regulated rivers: Examples from California, USA. *Geophysical Monograph* 89:165–176.

Kondolf, G. M., and R. R. Curry. 1986. Channel erosion along the Carmel River, Monterey County, California. *Earth Surface Processes and Landforms* 11:307–319.

Kondolf, G. M., and M. Larson. 1995. Historical channel analysis and its application to riparian and aquatic habitat restoration. *Aquatic Conservation* 5:109–126.

Kondolf, G. M., and W. V. G. Matthews. 1993. Management of coarse sediment in regulated rivers of California. Report No. 80. University of California Water Resources Center, Davis, California.

Kondolf, G. M., and M. L. Swanson. 1993. Channel adjustments to reservoir construction and instream gravel mining, Stony Creek, California. *Environmental Geology and Water Science* 21:256–269.

Kondolf, G. M., and P. R. Wilcock. 1996. The flushing flow problem: Defining and evaluating objectives. *Water Resources Research* 32(8):2589–2599.

Kondolf, G. M., and M. G. Wolman. 1993. The sizes of salmonid spawning gravels. *Water Resources Research* 29:2275–2285.

Kondolf, G. M., J. C. Vick, and T. M. Ramirez. 1996a. Salmon spawning habitat rehabilitation in the Merced, Tuolumne, and Stanislaus Rivers, California: An evaluation of project planning and performance. Report No. 90, University of California Water Resources Center, Davis, California.

Kondolf, G. M., J. C. Vick, and T. M. Ramirez. 1996b. Salmon spawning habitat rehabilitation on the Merced River, California: An evaluation of project planning and performance. *Transactions of the American Fisheries Society* 125:899–912.

Kuhl, D. 1992. 14 years of artificial grain feeding in the Rhine downstream the barrage Iffezheim. Pages 1121–1129 *in* Proceedings 5th international symposium on river sedimentation, Karlsruhe, Germany.

Lake County. 1992. Lake County aggregate resource management plan. Lake County Planning Department, Resource Management Division, Lakeport, California. Draft.

Laronne, J. B. 1995. Design of quarrying in the Shikma Reservoir, final report to Mekorot, Israeli Water Supply Company, Geography Department, Ben-Gurion University, Be'er Sheva, Israel. July, 15 pp. (in Hebrew).

Lehre, A., R. D. Klein, and W. Trush. 1993. Analysis of the effects of historic gravel extraction on the geomorphic character and fisheries habitat of the Lower Mad River, Humboldt County, California. Appendix F to the draft program environmental impact report on gravel removal from the Lower Mad River. Department of Planning, County of Humboldt, Eureka, California.

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

Los Angeles Times. 1992. Brothers get jail time for river mining. Article by Jonathan Gaw. 17 June.

Madej, M. A., and V. Ozaki. 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. *Earth Surface Processes and Landforms* 21:911–927.

Marcus, L. 1992. Status report: Russian River resource enhancement plan. California Coastal Conservancy, Oakland, California.

McBain, S. M., and W. Trush. 1996. Tuolumne River channel restoration project, special run pools 9 and 10. Report submitted to Tuolumne River Technical Advisory Committee (Don Pedro Project, FERC License No. 2299) by McBain and Trush, Arcata, California.

Morris, G. L. 1993. A global perspective of sediment control measures in reservoirs. *In* S. Fan and G. L. Morris (eds.), Notes on sediment management in reservoirs: National and international perspectives. US Federal Energy Regulatory Commission, Washington DC.

Northwest Hydraulics Consultants. 1995. Cache Creek streamway study. Unpublished report to Yolo County Community Development Agency, Woodland, California.

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

Parfitt, D., and K. Buer. 1980. Upper Sacramento River spawning gravel study. California Department of Water Resources, Northern Division, Red Bluff.

Parker, G., and P. C. Klingeman. 1982. On why gravel bed streams are paved. *Water Resources Research* 18:1409–1423.

Parsons Brinkerhoff Gore & Storrie, Inc. 1994. River management study: permanent protection of the San Luis Rey River Aqueduct crossings. Report to San Diego County Water Authority.

Partee, R. R., and Samuelson, D. F. 1993. Weyco-Brisco ponds habitat enhancement design criteria. Unpublished report, Grays Harbor College, Aberdeen, Washington.

Pauley, G. B., G. L. Thomas, D. A. Marino, and D. C. Weigand. 1989. Evaluation of the effects of gravel bar scalping on juvenile salmonids in the Puyallup River drainage. University of Washington Cooperative Fishery Research Unit Report. University of Washington, Seattle.

Potter, D. 1985. Sand sluicing from dams on the San Gabriel River—is it feasible? Pages 251–260 *in* J. McGrath (ed.), California's battered coast, proceedings from a conference on coastal erosion. California Coastal Commission.

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, California.

Reiser, D. W., M. P. Ramey, and T. A. Wesche. 1989. Flushing flows. Pages 91–135 *in* J. A. Gore and G. E. Petts (eds.), Alternatives in regulated river management. CRC Press, Boca Raton, Florida.

Richards, C., P. J. Cernera, M. P. Ramey, and D. W. Reiser. 1992. Development of off-channel habitats for use by juvenile chinook salmon. *North American Journal of Fisheries Management* 12:721–727.

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

Sandecki, M. 1989. Aggregate mining in river systems. *California Geology* 42(4):88–94.

Schick, A. P., and J. Lekach. 1993. An evaluation of two ten-year sediment budgets, Nahal Yael, Israel. *Physical Geography* 14(3):225–238.

Schumm, S. A. 1977. The fluvial system. John Wiley & Sons, New York.

Scott, K. M. 1973. Scour and fill in Tujunga Wash—a fanhead valley in urban southern California—1969. US Geological Survey Professional Paper 732-B.

Sear, D. A., and D. R. Archer. 1995. The effects of gravel extraction on the stability of gravel-bed rivers: A case study from the Wooler Water, Northumberland, UK. Paper presented to the 4th workshop on gravel bed rivers. Gold Bar, Washington.

Sen, S. P., and A. Srivastava. 1995. Flushing of sediment from small reservoir. Pages 149–154 *in* Proceedings of sixth international symposium on river sedimentation, New Delhi, India.

Sonoma County. 1992. Sonoma County aggregate resources management plan and environmental impact report, draft. Prepared by EIP Associates for Sonoma County Planning Department, Santa Rosa, California.

Stevens, J. C. 1936. The silt problem. Paper No. 1927. Transactions American Society of Civil Engineers.

Stevens, M. A., B. Urbonas, and L. S. Tucker. 1990. Public–private cooperation protects river. *APWA Reporter* September: 25–27.

Stone, K. E., and B. S. Kaufman. 1985. Sand rights, a legal system to protect the shores of the beach. Pages 280–297 *in* J. McGrath (ed.), California's battered coast, proceedings from a conference on coastal erosion. California Coastal Commission.

Taig, M. 1996. Use of sediment accumulated in flood reservoirs. Pages 25–30 *in* J. B. Laronne (ed.), Reservoirs as a source of water for the Negev Conference Proceedings. Ben-Gurion University, Be'er Sheva, Israel (in Hebrew).

Todd, A. H. 1989. The decline and recovery of Blackwood Canyon, Lake Tahoe, California. *In* Proceedings, international erosion control association conference. Vancouver, British Columbia.

Vick, J. 1995. Habitat rehabilitation in the Lower Merced River: A geomorphological perspective. Masters thesis in Environmental Planning, Department of Landscape Architecture, and Report No. 03-95, Center for Environmental Design Research, University of California, Berkeley.

Westrich, B., S. Al-Zoubi, and J. Muller. 1992. Planning and designing a flushing channel for river reservoir sediment management. Pages 861–867 *in* 5th international symposium on river sedimentation. Karlsruhe, Germany.

Wilcock, P. R., G. M. Kondolf, W. V. Matthews, and A. F. Barta. 1996. Specification of sediment maintenance flows for a large gravel-bed river. *Water Resources Research* 32(9):2911–2921.

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