WHITE PAPER

Freshwater Gravel Mining and Dredging Issues

Prepared for

Washington Department of Fish and Wildlife
Washington Department of Ecology
Washington Department of Transportation

April 2002

WHITE PAPER

Freshwater Gravel Mining and Dredging Issues

Prepared for

Washington Department of Fish and Wildlife
Washington Department of Ecology
Washington Department of Transportation

Prepared by

G. Mathias Kondolf
Matt Smeltzer
Lisa Kimball

Center for Environmental Design Research
390 Wurster Hall
University of California
Berkeley CA 94720

December 10, 2001

Contents

Tables

Figures

Introduction and Scope

Sediment is mechanically removed from river channels in Washington State for a variety of reasons: to improve navigation, agricultural drainage, flood control, channel stability, and production of construction aggregate. In this white paper, we review the scientific information regarding the effects of these activities.

Extraction of sand and gravel for construction aggregate is the largest mining industry in most states – not only in volume but also in value. As the environmental impacts of aggregate extraction from river channels become increasingly well understood, the practice has received increased scrutiny, especially in salmon-bearing rivers and streams. For Washington State, the supply of sand and gravel from various sources by geologic province, and environmental impacts of extraction from channels and floodplains have been summarized in excellent reviews by Dunne et al. (1981), Bates (1992), Collins (1995), and Norman et al. (1998). The purpose of this report is to build upon existing literature for Washington and elsewhere to summarize current scientific information regarding the environmental effects of mining gravel and sand for construction aggregation from rivers and streams, along with the effects of other freshwater dredging. The emphasis is on effects on salmonids in their various freshwater-based life stages, to provide a scientific basis for future development of guidelines that will be protective of the resource.

This document does not make policy recommendations, but summarizes the scientific literature and unpublished research on gravel mining effects in Washington state and elsewhere. It also draws upon discussions with resource managers, site visits, and analysis of historical aerial photographs and maps of selected sites. There is relatively little literature on this subject in international, peer-reviewed journals, though the body of work expands once agency technical reports and similar "gray" sources are included. As an efficient, easily read and comprehended format for presenting the literature review, we prepared a table summarizing our literature review (Appendix A), which complements the topical-based review in the text. The purpose of this white paper is to summarize the scientific information that will serve as the basis for future guidance documents.

Gravel Supply, Transport, and River Processes

As background to set the context for discussion of impacts from gravel mining and channel dredging, this introductory section reviews sediment yield, sediment transport and storage in river systems, channel form and movement, and their implications for habitat. The reader is also referred to Miller et al. (2001) for a review of channel form and process.

Erosion/Sediment Yield

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. Supply of sand and gravel is influenced by 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 and other effects of in-channel and floodplain gravel mining and freshwater dredging.

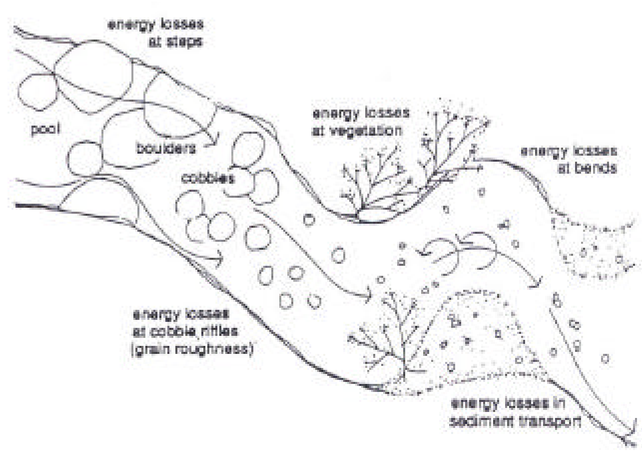

Figure 1. Diagram of energy of dissipation in river channels (source: Kondolf 1997).

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 et al. 1964). Bedload ranges from a few percent of total load in lowland rivers, to perhaps 15 percent in mountain rivers (Collins and Dunne 1990), to over 60 percent in some arid catchments (Schick and Lekach 1993). Although a relatively small part of the total sediment load in most rivers, 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). Total bedload may consist primarily of sand, in contrast with the more visible and ecologically important coarser bedloads, gravel and cobbles.

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.

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 (3.9 x 10^{-4}in/yr) (Leopold et al. 1964), the central Sierra Nevada of California about 0.1 mm/yr (3.9 x 10^{-3} in/yr) (Kondolf and Matthews 1993), the Southern Alps of New Zealand about 11 mm/yr (0.4 in/yr) (Griffiths and McSaveney 1983), and the southern Central Range of Taiwan over 20 mm/yr (0.8 in/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 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. Over time scales of centuries, the river channel in the transport reach can be likened to a "conveyor belt", which transports the erosional products downstream to the ultimate depositional sites below sea level. Transport of sediment is highly flow dependent, an "event-based" process that varies widely from year to year. At time scales of years to decades, the transport of sediment tends to be episodic, in contrast to the continuous transport implied by the conveyor belt analogy. Moreover, individual grains may not move very far per flood – often jumping just from one bar to the next bar downstream, and material transport is heterogeneous spatially within the channel. Thus the conveyor belt analogy, while useful in emphasizing upstream-downstream linkages, may imply a static, repetitive, easily manipulated mechanical phenomenon – which clearly is not the case.

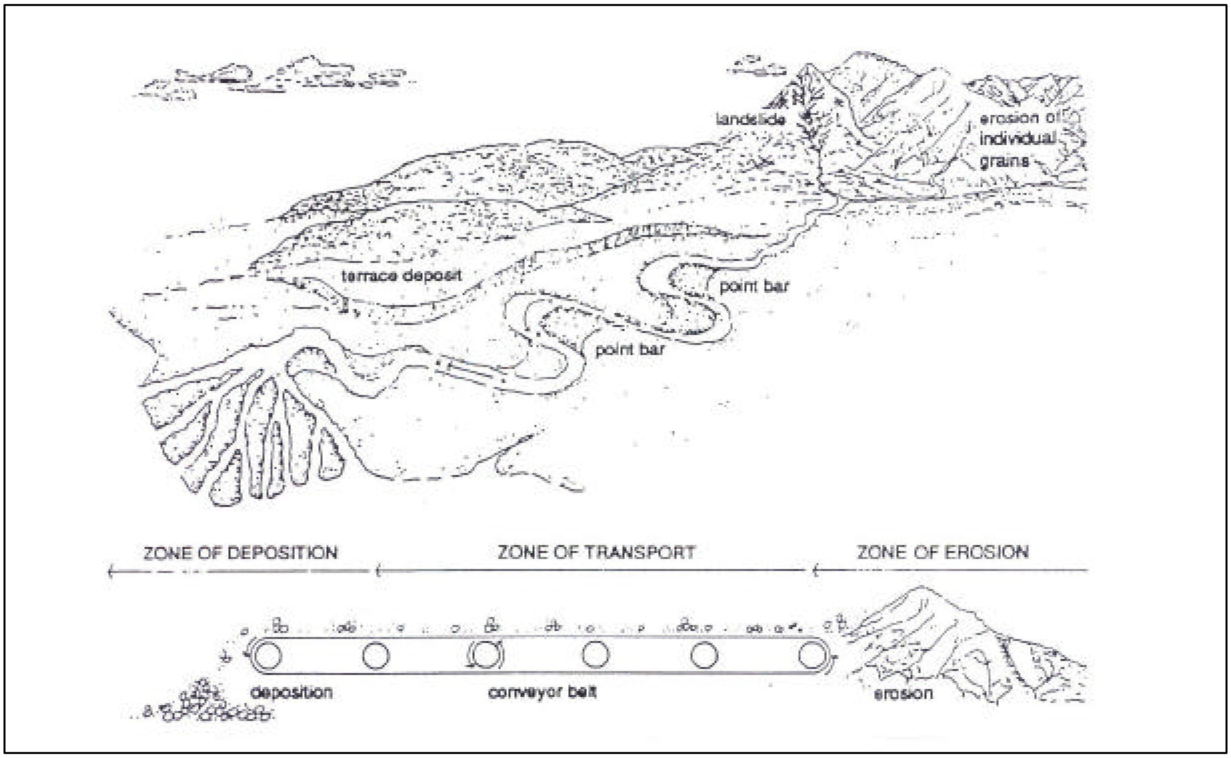

Figure 2. Zones of erosion, transport, and deposition (after Schumm 1977), and the river channel as conveyor belt for sediment. (Reprinted from Kondolf 1994, with permission.)

Transport of sediment through the catchment and along the length of the river system is continuous (on geologic time scales). Increased erosion in 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).

Rivers and streams draining the western slope of the Cascade Mountains in Western Washington typically transition abruptly from steep, eroding uplands to relatively flat coastal plains. Gravel mining activities are typically situated near urban areas in these transitions, where the coarse portion of the sediment delivered from steep uplands during floods is deposited. These are also typically zones of naturally pronounced channel activity.

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.

As discussed below, the "conveyor belt" has been interrupted in many Washington rivers by dams (e.g. Yakima, Cle Elum, Columbia, Tolt, Wynoochee, Elwha, Cowlitz, Tieton), so the continuity of sediment transport has been disrupted.

Channel Form, Channel Migration, and Riverine Habitats

A distinction is commonly made among the active channel, floodplain (commonly inundated every 2 years or so, although this frequency is highly variable), and terraces or "abandoned floodplains" (which are inundated only in larger, less-frequent floods). The zone within which the active channel migrates is commonly termed the "meander belt" or "channel migration zone."

Geomorphic features of the channel and floodplain, interacting with a variable flow regime, create a distinct suite of aquatic and riparian habitats. Diverse aquatic habitats result from channel complexity and connectivity with adjacent floodplain surfaces, such that at any flow level (from base flow to big flood), there exist a diversity of depths, velocities, and substrates, including micro-habitats protected from the full force of the current at high flows. Floodplain water bodies such as oxbow lakes, wallbase channels, spring creeks, and other side channels are also important sites for biodiversity (Figure 3) (Piégay et al. 2001, Greco 1999). Floods are essential for riverine health, as they drive channel migration, bank erosion, deposition of bars, deposition of overbank sediments, and channel avulsion. As channels naturally migrate across their floodplains, they maintain roughly the same dimensions, with erosion on the outside bend being balanced by bar deposition and yielding a characteristic distribution of grain size and hydrologic condition, and a characteristic stratigraphy of fine-grained overbank sediments overlying channel gravels (Figure 4). This dynamic fluvial process serves to rejuvenate gravel quality and channel and floodplain forms, add woody debris to the channel, build complex channel forms, and create fresh bar and floodplain surfaces for riparian vegetation establishment. Channel migration is thus a key process for creating and maintaining ecological diversity along many rivers, but in populated areas, it can conflict with human expectations of a static riverbank.

Along many channels, riparian vegetation provides shade, overhanging banks, woody debris, and allochthonous food (e.g., leaves and insects that fall into the channel from the banks and overhanging branches). During floods, flooded riparian forests provide food, refugia from high velocity currents, and cover. Riparian vegetation establishes in response to favorable conditions such as suitable substrate, soil moisture (generally a high water table), timing of seed dispersal with respect to the hydrograph, freedom from scour in the first years of growth, and freedom from grazing or excessive competition from other plants, with different species adapted to different suites of condition. The diversity of riparian habitat depends upon the diversity of physical environments for vegetation establishment, ranging from freshly deposited, coarse-grained point bars (colonized by early successional species) to higher floodplain surfaces

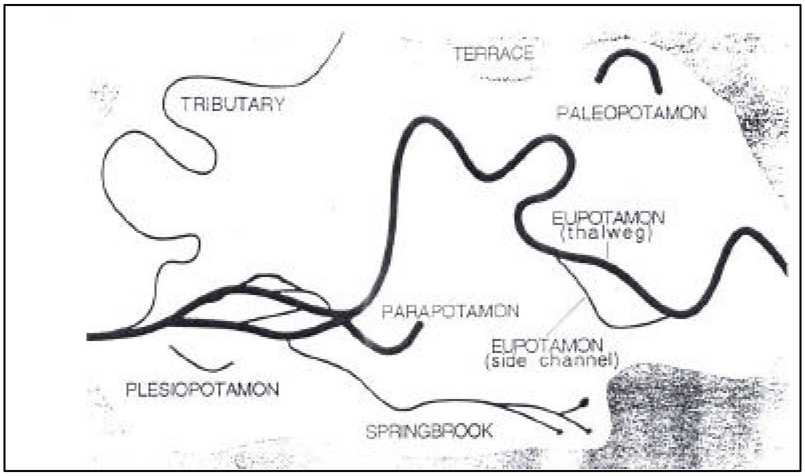

Figure 3. Floodplain habitats in an actively migrating channel. (Adapted from Ward and Stanford 1995).

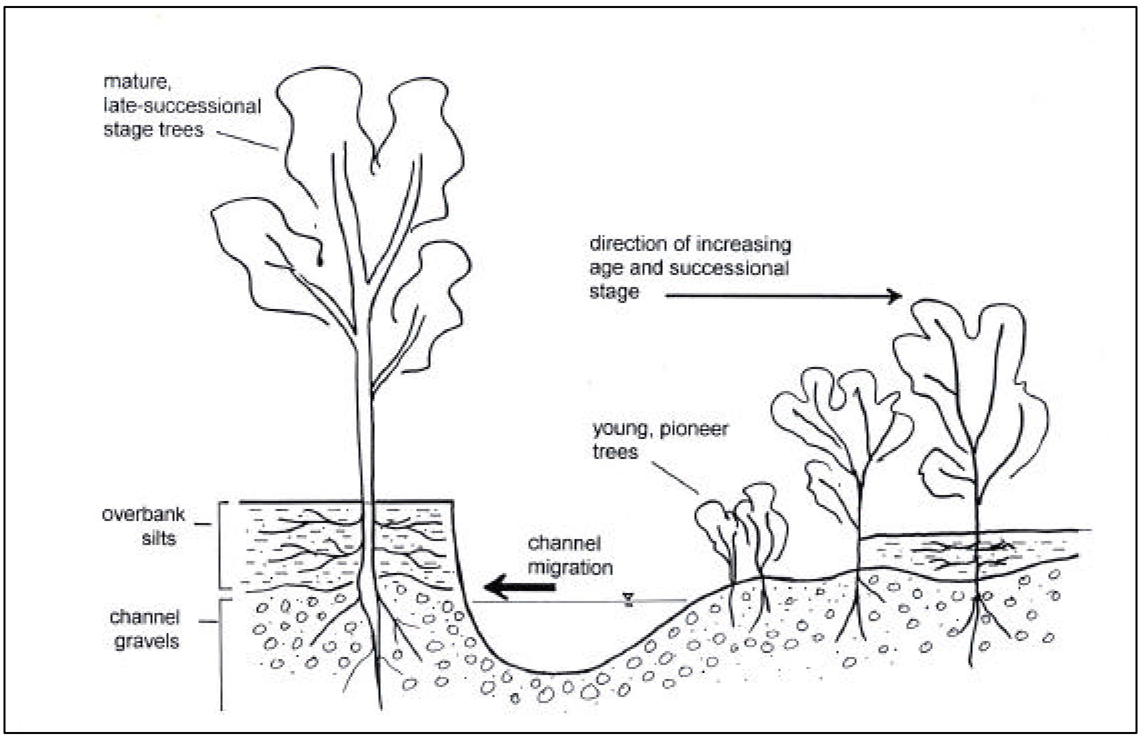

Figure 4. Diagram of floodplains building along a meandering river, producing a characteristic stratigraphy of basal gravels (channel deposits), overlain by sand (point-bar deposits), in turn overlain by silt and fine sands (overbank deposits).

The age and successional stage of vegetation generally increase with increasing age and elevation of the geomorphic surface, from the young pioneer plants on the freshly deposited point bar to the mature, equilibrium-stage vegetation on thick overbank silts on the floodplain distant from the current channel location.

underlain by fine-grained overbank sediments (supporting mature, later successional species) (Figure 4).

On many gravel bed rivers, woody riparian vegetation typically establishes in a narrow band along the channel margin, in the "window of opportunity" between the zone of frequent scour and the zone of desiccation during the dry season (Figure 5) (Kondolf and Wilcock 1996). Seedlings that begin to grow on high surfaces will probably not succeed because of desiccation during the dry season, while seedlings that begin to grow on the active channel bed will likely be scoured by floods.

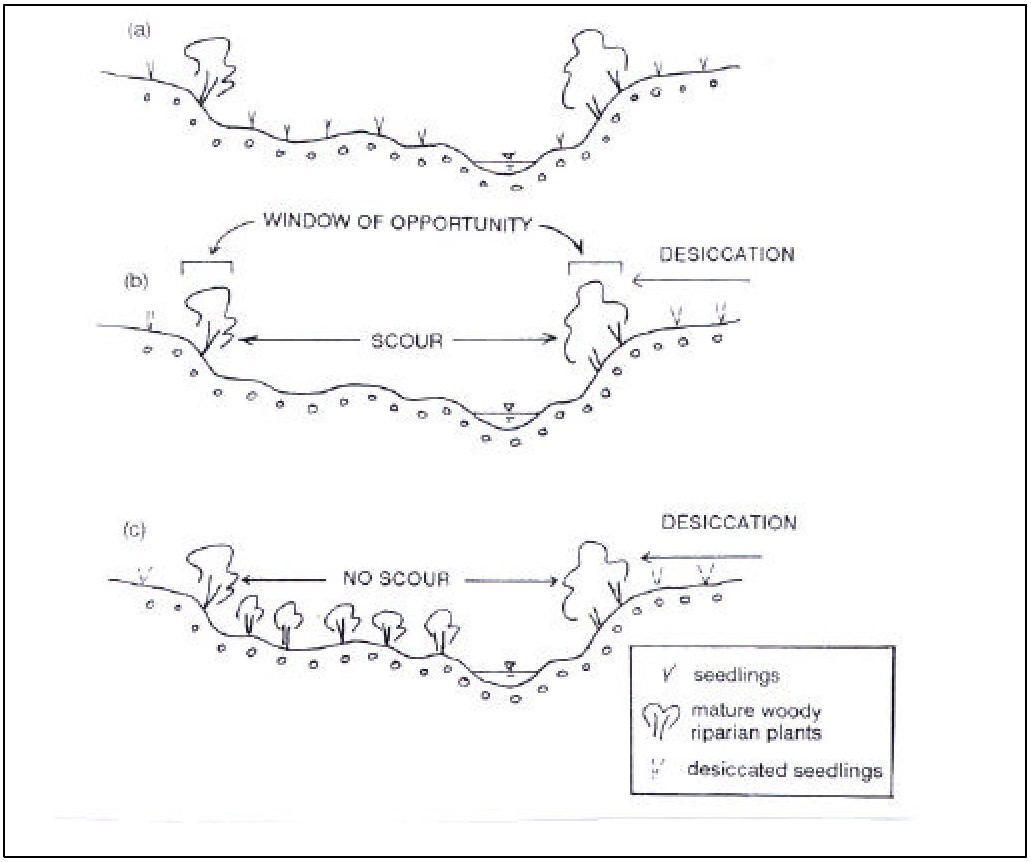

Figure 5. Schematic diagram (Source: Kondolf and Wilcock 1996).

(a) seedling distribution following annual flood recession, (b) the "window of opportunity" for establishment of riparian vegetation between the zone of scour and zone of desiccation in an unregulated channel, and (c) encroachment of vegetation into the channel after reduction of flood peaks by an upstream reservoir and elimination of scour.

As channels migrate naturally, banks are undercut and mature trees (cottonwoods, valley oaks, etc.) fall into the channel and thereby become large woody debris (LWD). While the term "debris" recalls the negative connotations of wood in the river associated with navigation hazards and potential impacts to bridges and other infrastructure during floods, the ecological role of LWD is becoming increasingly recognized, especially for creating habitat for salmonids

(Harmon et al. 1986). As a potentially sustainable and environmentally beneficial alternative to removing wood from channels, infrastructure can be modified to permit wood to pass during floods, thereby permitting wood to remain in channels for ecological purposes. Recruitment of LWD by channel migration depends not only on the rate of channel migration, but also the extent, distribution, and characteristics of the riparian forest.

The role of frequent flooding and dynamic channel migration in supporting ecological diversity should not be underestimated. It is the ability of channels to erode and deposit, to recruit woody debris and form complex pools, bars, and other channel forms, and to create a diversity of surfaces for riparian colonization, and the interaction of a variable flow regime with these dynamically evolving forms that makes possible high ecological diversity. The diversity of these physical habitats is maintained by active channel migration, with the greatest diversity present in the actively migrating, meandering rivers (Figure 6) (Ward and Stanford 1995, Poff et al. 1997). If channel dynamics are arrested by bank protection, overbank flooding reduced by levees, or flooding and active channel movement reduced by flow regulation by upstream reservoirs, ecological diversity (at least of native species) is likely to suffer (Johnson 1992, Baltz and Moyle 1993).

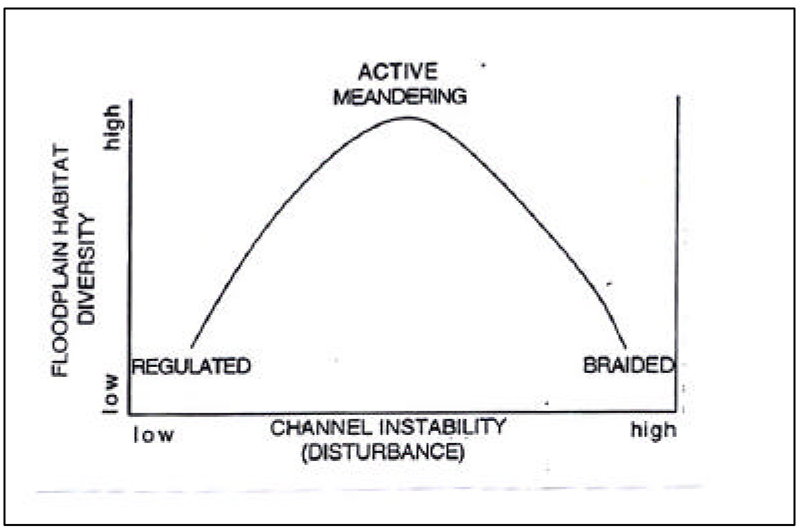

Figure 6. Habitat diversity as function of channel stability. (Source: Ward and Stanford 1995.)

Residential and commercial development of river floodplains and terraces in Washington State has led to a conflict between river management to reduce flood hazard and bank erosion on one hand, and management for river processes that maintain sediment transport continuity and create riparian and aquatic habitat on the other hand. Levees and bank protection works prevent channel migration that would naturally erode floodplain and terrace deposits, and simultaneously deposit sediment to form new floodplain surfaces, creating habitat essential to fluvial ecosystem health. By “fixing” a river in place, levees and bank protection create a “lost opportunity” for habitat creation. From a geomorphic perspective, 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. (See Floodplain/Riparian Issues White Paper prepared by Susan Bolton).

Effects of Dams and Gravel Extraction on Sediment Transport Continuity

Dams disrupt the longitudinal continuity of the river system and interrupt the action of the "conveyor belt" of sediment transport. 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, whose nature depends upon the characteristics of the original and altered flow regimes and sediment loads.

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 so long as the reservoir continues to trap more sediment, the water released 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 (termed *armoring* in fluvial geomorphology) until equilibrium is reached and the material cannot be moved by the flows (Kondolf 1997). Small "run-of-the-river" diversion dams may fill with sediment and thereafter pass sediment (including bedload) downstream.

Reduction in bedload sediment supply can induce a change in channel pattern, as illustrated on Stony Creek, a tributary to the Sacramento River 200 km (125 mi) 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. In the reach below the dam, the present channel erodes from the banks the equivalent of about 20% of its former sediment load (now all trapped behind the dam) on an annual average basis (Kondolf and Swanson 1993). Reservoirs also may reduce flood peaks downstream, potentially reducing the effects of hungry water, inducing vegetation encroachment, channel shrinking, or allowing fine sediments to accumulate in the bed.

The reduced sediment supply below dams has profound implications for the siting of sand and gravel mines, because mines located in sediment starved reaches below a dam are not replenished by sediment yield from the basin, only by downstream tributaries and channel erosion. Thus, incision and channel erosion are likely to be most severe in sediment-starved reaches below dams.

Effect of Dams on High Flow Regime and Channel Geomorphology and Ecology

Dams can have profound effects on downstream channel form through changing flow regime, sediment load, and the flux of large woody debris. The changes in river flows induced by dams can be highly variable, depending on the dam size and operations. 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. Most commonly, floods (especially frequent floods) are reduced, seasonal flow regimes altered, and the relative timing of tributary and mainstem flooding altered, leading to desynchronization of tributary and mainstem flows. Even small diversion dams can reduce flow regimes on downstream channels sufficiently to produce changes in channel geometry (Miller et al. 2001).

By reducing the magnitude and frequency of floods, dams reduce the dynamic nature of river behavior downstream. Disturbance in riverine ecosystems (e.g. Resh et al. 1988, Sparks et al. 1990), especially "intermediate" level disturbances such as annual or biannual scouring floods, are essential for maintaining species richness (Connell 1978, Picket and White 1985). Native fishes are adapted to natural flow regimes, and substitution of steady, regulated flows for naturally variable flows has probably facilitated establishment of exotic fish species that prey upon salmon below dams in California (Baltz and Moyle 1993). If a dam reduces the frequency of scour in gravel bed rivers, riverine food webs can be altered by increases in predator-resistant but scour-vulnerable invertebrates, diverting energy away from the food chain supporting valued fish such as salmon and trout (Wootton et al. 1996, Power at al. 1996).

High flows maintain distribution, abundance, and diversity of species and successional stages of riparian vegetation (Scott et al. 1996, Hupp and Osterkamp 1996), and reductions in high flows below dams can lead to reduced channel migration and declines in riparian habit (Shields et al. 2000, Johnson 1992). Downstream of reservoirs, 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). As illustrated in Figure 5, seedlings established in the active channel during the seasonal recession limb are normally scoured out by the next winter's floods. However, dam-induced reduction in floods may permit woody vegetation to become permanently established in the active channel, where it decreases channel capacity, stabilizes the river in place, and eliminates open gravel bar habitats essential for some species. Channel narrowing has been greatest below reservoirs that are large enough to contain the river's largest floods.

In many cases, reduction of flood peaks can more than offset reduced sediment availability, causing net aggradation of the river channel below the dam (Kellerhalls 1982). Fine sediment delivered to the river channel by tributaries may accumulate in the bed, degrading spawning gravels and filling pools, because there are no more natural floods to flush fine sediments from the river bed (Milhous 1982). A well-documented example of this occurred on the Trinity River after 1960, below Trinity and Lewiston Dams, California, where fine sediment from tributaries affected by timber harvest accumulated in the channel bed, filling pools and interstices of gravel and cobble riffles (Wilcock et al. 1996).

Salmon Use of Gravel-Bed Rivers

Salmon Life Cycle and the Role of Gravel

Salmonids (members of the family *Salmonidae*) may be migratory or nonmigratory, but all use freshwater stream or lakeshore gravels for spawning (Figure 7). Many salmonids are anadromous, having evolved life histories in which adult years are spent in the open ocean with its plentiful food, while incubation of embryos takes place in the relative safety of freshwater streambed gravels. Within this general pattern, there is a wide range of inter- and intra-specific variation in life histories (Groot and Margolis 1991). Some anadromous fish spend their first year or two in freshwater, only migrating to the sea after they have passed the more vulnerable juvenile phase. Other salmonids, mostly trout and kokanee (landlocked sockeye) salmon, reside in freshwater for their entire lives. Another important characteristic of salmonids is their limitation to coldwater systems. Temperature is limiting in many streams, but is a topic beyond the scope of this paper (Allen 1969, Bjornn and Reiser 1991).

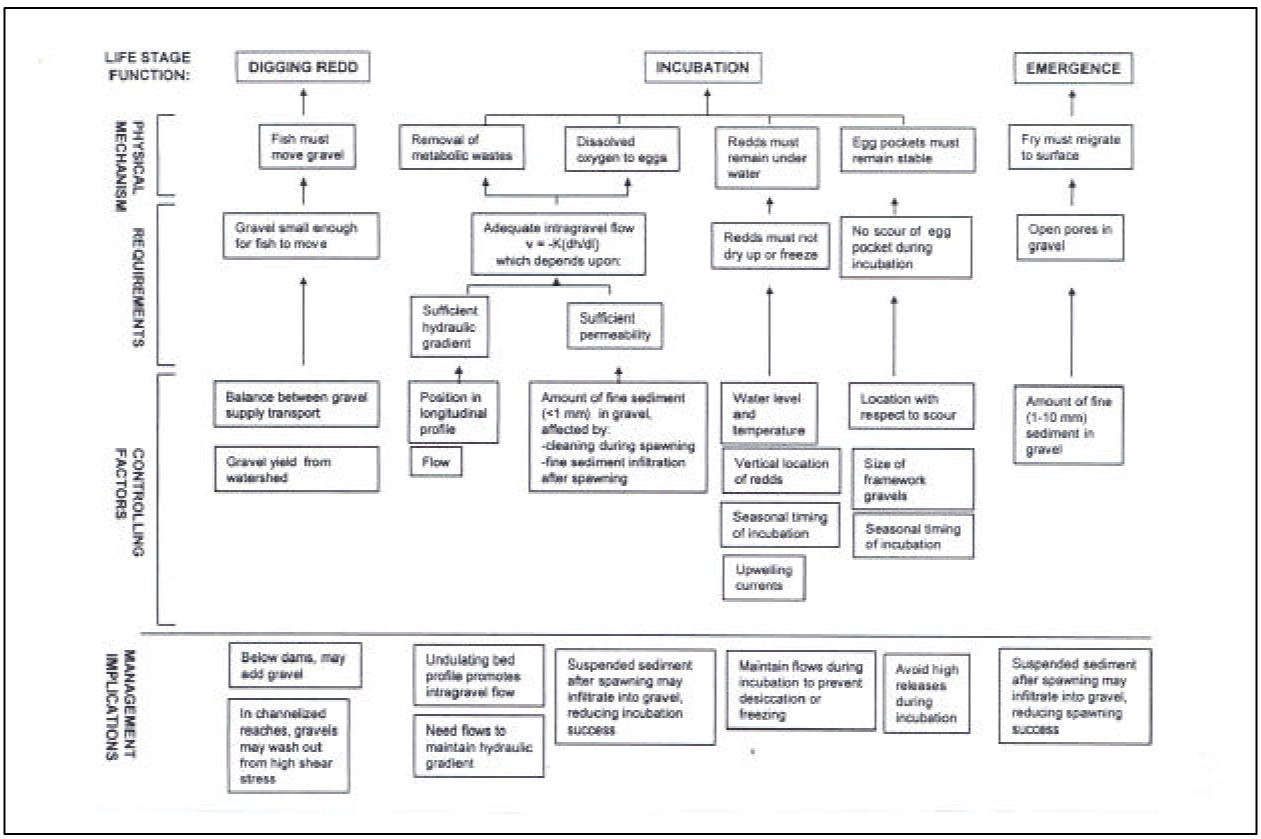

Figure 7. Flow chart showing gravel requirements of salmonids during redd construction, incubation, and emergence (Source: Kondolf 2000).

Migration

For successful propagation of anadromous salmonids, adults must successfully migrate upstream to spawning grounds, smolts downstream to the ocean. Adult salmonids are capable of passing through or jumping over many obstacles. In contrast to the energetic swimming and jumping of upstream-bound adults, oceanward-migrating smolts are weak swimmers and essentially ride the current downstream to the ocean.

Even under natural conditions, barriers such as bedrock falls limit the upstream extent of anadromy in most rivers (e.g., Snoqualmie Falls). Of human-imposed, artificial barriers, dams are probably the most pervasive and have cut off the greatest area of spawning habitat. Other artificial barriers include low diversion dams (including temporary brush dams), and excessively shallow water or even dry streambeds resulting from diversions or mechanical disruption of the bed and loss of channel confinement, reaches of low dissolved oxygen, and cross-channel nets. Upstream migrating adults can also fail in reproduction by following artificial dead-ends, such as canals carrying irrigation return flow. Smolts migrate seaward with the flowing water, so their progress is affected not so much by barriers per se, but rather by mortality from factors such as passage over dams or through hydroelectric turbines, diversion into irrigation ditches, post-flood stranding in off-channel water bodies such as captured gravel pits, excessive water temperatures, and predation.

Spawning, Incubation, and Emergence

In all species, the female deposits her eggs in a nest in the gravel termed a *redd*. Construction of the redd varies slightly among salmonids, but the process is the same in its basic elements. The female turns on her side and places her tail either directly on or within a few centimeters above the gravel, and, with an abrupt muscular contraction, lifts her tail rapidly upward from the gravel several times in rapid succession. This action is termed “fanning,” “cutting” (Needham 1961), or “digging” (Burner 1951, Briggs 1953), produces an upward suction force and lifts gravel particles from the bed. Once lifted, these particles are exposed to the current, and they are carried downstream (usually for a distance of some tens of centimeters) before they are redeposited. The female repeats this digging at intervals that vary among species and stocks. For example, on Prairie Creek, California, coho salmon were observed to fan at intervals of 2-3 minutes, Chinook salmon at intervals of more than 5 minutes, and steelhead trout at intervals of 30-90 seconds (Briggs 1953).

The result of this digging and redistribution of gravel is the characteristic redd form: upstream, a depression in the gravel, termed the pit or pott, and, downstream, a mound of gravel termed the tailspill (Hobbs 1937, Burner 1951). Redds are typically oblong in shape, reflecting the role of the current in constructing the redd. The deepest part of the pit tends to have the coarsest gravels, as smaller, more mobile gravels have been carried downstream to the tailspill. The tailspill gravels are of relatively uniform size because the coarser gravels, too large to be moved by the current, were left behind in the pit as a lag deposit, and the finer sediment has been washed away by the current. After excavating the pit, the female drops into the pit, the male positions himself beside her, and eggs and milt (sperm) are expressed.

Currents in the redd are characterized by a weak upstream eddy, which allows eggs and milt to move to the bottom of the pit (Hobbs 1937, Burner 1951). In some cases, redds are located in areas where downwelling currents exist and may help to draw the milt down into the gravel to fertilize the eggs (Stuart 1953). If the bed material includes particles too large for the female to move, these rocks will remain as coarser lag deposits on the bottom of the pit. The interstices of these large particles make excellent sites for lodgment of eggs (Hobbs 1937, Burner 1951). As a result, the egg pocket in a redd may be composed of a coarser gravel than the rest of the redd (Chapman and McLeod 1987).

Immediately after the spawning act, the female resumes digging upstream, loosening gravels, which are then carried into the pit, covering the eggs. The female may continue digging, progressing upstream, depositing several egg pockets within one redd. In seven chinook salmon redds excavated by Hawke (1978), from 4 to 6 egg pockets were found, nearly all aligned parallel to the current direction. Of eleven brown trout redds excavated by Hardy (1963), two contained no egg pockets, and nine contained 2-5 egg pockets each, nearly all aligned parallel to the current direction. One female may also dig (and spawn in) more than one redd in different spots (Reingold 1965, Cederholm and Salo 1979, Van den Berge and Gross 1984), or dig false redds, in which she never spawns (e.g., Briggs 1953, Hardy 1963).

As might be expected, the size of redds constructed, the depth of egg burial, and the size of particles that can be moved varies with size of the fish. This relation is visible when comparing species of different sizes (e.g., Burner 1951) or different-sized individuals of the same species (e.g., Ottaway et al. 1981, Van den Berge and Gross 1984). In general, it can be said that larger fish make bigger redds, bury their eggs deeper, and can move larger rocks than smaller fish. This is due not only to the greater upward force they can exert on the bed, but also to the fact that they can spawn in stronger currents. These currents assist in dislodging and moving gravels downstream.

The eggs incubate in the gravel for a period of weeks to months (depending on temperature), and hatch. Newly hatched fish, termed alevins, continue to live in the gravel and grow, taking nourishment from an abdominal yolk sac. Both embryos and alevins depend on circulating intragravel waters to supply them with dissolved oxygen and to carry off metabolic wastes. When the alevins are ready to emerge, they must migrate up to the surface through interstices in the gravel. Resident (non-migratory) fish may spend their entire lives within a few hundred meters of the redd, or migrate vast distances through lakes and rivers. Anadromous fish may spend a juvenile period of a year or two in freshwater before migrating to the ocean, or they may migrate almost at once upon emergence, depending on the species (Everest 1987).

Gravel Size Requirements for Salmonid Reproduction

The gravel size requirements of salmonids depend on the life stage and the specific ways the fish use the streambed in each life stage (Kondolf 2000), as discussed below and illustrated in Figure 7.

Salmonids tend to spawn in streambed gravels that are relatively clean and mobilized every year or two. Measurements of gravel sizes reported in the literature for Washington State suggest steelhead trout use gravels with median diameters from 10 to 40mm (0.40-1.6in), Chinook salmon 34-54mm (0.3-2.1in), and coho salmon 10-35mm (0.40-1.4in) (Table 1).

Table 1. Median and geometric mean diameters of salmonid spawning gravels reported for Washington State (Source: Kondolf and Wolman 1993).

Entry No. [a]	Species	River		Fish Length (mm)	D_{50} (mm)	d_g (mm)	Reference
REDDS							
26	Steelhead	Kalama River		75	31	23.5	Chambers et al. 1954, 1955
35	Chinook	Kalama River		86	54	39.5	"
37	Chinook	Cispus River		82	50	35.1	"
39	Chinook	American River		82	35	25.6	"
40	Chinook	Cowlitz		82	51	29	"
41	Coho	Spring Creek		65	35	20.3	"
42	Coho	Toutle River		65	16.5	15.2	"
43	Coho	Burns Creek 1953		65	29	21	"
44	Coho	Burns Creek 1954		65	33	22.1	"
53	Sockeye	Little Wenatchee River		50	17.8	13.4	"
POTENTIAL SPAWNING GRAVELS							
66	Steelhead	Kalama River		75	40	28.1	"
69	Steelhead	Stequaleho Creek	site 1	65	19.5	10.9	Cederholm and Salo 1979
70	Steelhead	"	site 2	65	22	11.7	"
71	Steelhead	"	site 3	65	22	12	"
72	Steelhead	Clearwater River	site 1	70	10.4	9.3	"
73	Steelhead	"	site 2	70	13.5	9.3	"
74	Steelhead	"	site 3	70	18	9.6	"
75	Steelhead	"	site 4	70	19	9.8	"
76	Steelhead	"	site 5	70	23	11.2	"
77	Steelhead	"	site 6	70	15	10.8	"
78	Steelhead	"	site 7	70	10.2	8.4	"
83	Chinook	Columbia River		86	78	41.4	Chambers et al. 1954, 1955
85	Chinook	Kalama River		86	49	30.6	"
86	Chinook	Cowlitz River		82	42	25.5	"
88	Chinook	Cispus River		82	37	23.2	"
89	Chinook	American River		82	34	24.3	"
113	Coho	Spring Creek		65	13	10.4	"
114	Coho	Toutle River		65	10	8.8	"
115	Coho	Burns Creek 1953		65	29	24	"
116	Coho	Burns Creek 1954		65	33	25.3	"

[a] Entry no. refers to entry no. in Tables published by Kondolf and Wolman (1993)

The gravel sizes preferred by spawning salmonids are similar to the sizes typically exploited by commercial gravel miners, as illustrated in Figure 8 from Bates (1987). Thus, commercial gravel mining can preferentially reduce the availability of spawning-sized gravel in river channels.

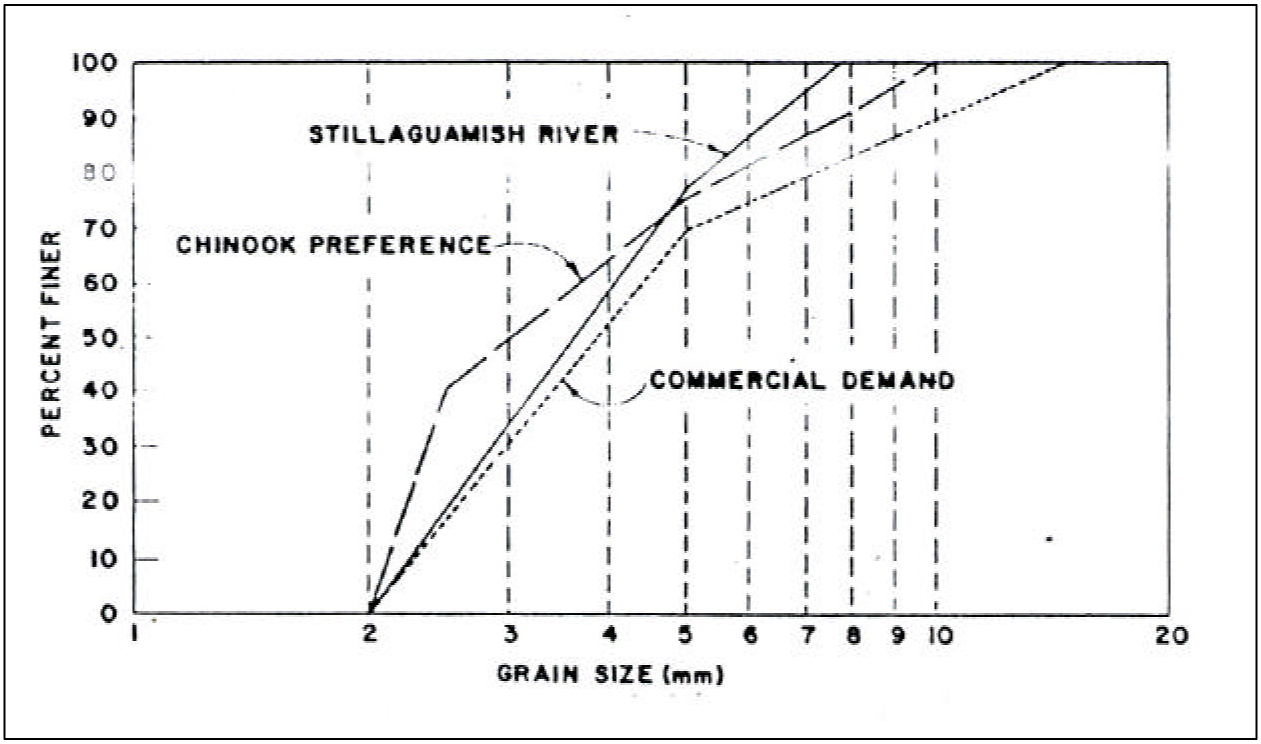

Figure 8. Diagram showing gravel sizes preferred by spawning salmonids and commercial gravel miners (Source: Bates 1987).

Redd excavation

In initially digging the redd, the spawning female must be able to move gravels to excavate a depression in the bed. While the fish need not move all rocks present (some larger particles can remain unmoved as a lag deposit), most of the particles present must be movable or the redd cannot be excavated. Thus, most framework grains should be movable, a requirement that effectively sets an upper size limit to suitable spawning gravels. Larger fish are capable of moving larger rocks, so this upper size limit varies with fish size (Figure 9) (Kondolf and Wolman 1993).

Below reservoirs, gravels may become too coarse for spawning, due to bed armoring. Gravel is trapped in reservoirs, and the sediment-free water released downstream may winnow smaller, mobile grains from the bed, leaving only particles too coarse for use by spawning salmon, as documented on the Sacramento, Shasta, and Klamath Rivers in California (Parfitt and Buer 1980, Buer et al. 1981).

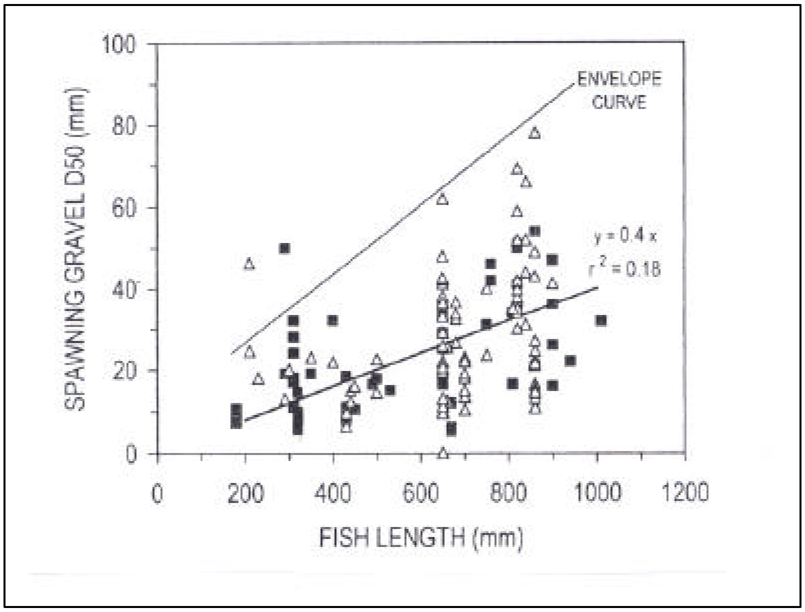

Figure 9. Median diameter (d_{50}) of spawning gravel plotted against body length of a spawning salmonid. (Modified from Kondolf and Wolman 1993).

Solid squares denote samples from redds; open triangles are "unspawned gravels," which are potential spawning gravels sampled from the undisturbed bed near redds.

Incubation

For successful incubation, gravel must be sufficiently free of fine sediment that the flow of water through the gravel is adequate to bring dissolved oxygen (DO) to eggs and carry off metabolic wastes (see discussions in Groot and Margolis 1991, Chevalier et al. 1984). Studies relating intragravel water properties to emergence success indicate that *minimum* levels of DO necessary for survival vary (with temperature, in part), but generally fall between 2 and 8 $mg \cdot l^{-1}$ (Alderdice et al. 1958, Coble 1961, Shumway et al. 1964, Silver et al. 1965, Davis 1975, Chevalier et al. 1984). Other studies have shown that interstitial fine sediment can reduce gravel permeability and lead to less intragravel flow, which can result in lower levels of DO and suffocation of embryos (McNeil and Ahnell 1964, Cooper 1965, Koski 1966, Chevalier et al. 1984). Thus, for successful incubation, the lower limits of acceptable spawning gravel size are defined not by framework size, but by the amount of interstitial matrix present (and its effect on permeability).

Chinook salmon (and some other salmonids) have been observed to preferentially spawn where stream water downwells into the gravel bed (e.g., Vronskiy 1972), while other species (such as chum salmon *O. keta*) often spawn where water upwells from the gravel bed into the water column (e.g., Tautz and Groot 1975). As emphasized by Healey (1991), the absence of downwelling or upwelling currents may be an important reason why spawning fish do not use many seemingly excellent spawning gravels (e.g., Burner 1951).

Dye studies in the field and laboratory have confirmed that irregularities in the bed profile tend to promote exchanges of water between the stream and the interstices of the gravel bed (Vaux 1968, Cooper 1965). These patterns can be explained by a fundamental equation of groundwater flow, Darcy's Law, which states that the rate of groundwater flow (or Darcy velocity, *V*) is the product of the permeability (or hydraulic conductivity, *K*) and the hydraulic gradient *dh/dl* (Figure 10) (Freeze and Cherry 1979). The lower elevation of the water surface in the riffle creates a hydraulic gradient that induces downwelling at the tail of the pool. The redd mound (or tailspill) produces a similar effect at a smaller scale, inducing inflow of stream water into the mound. (Darcy's law also illustrates the importance of the matrix sediment, as it affects the hydraulic conductivity, *K*).

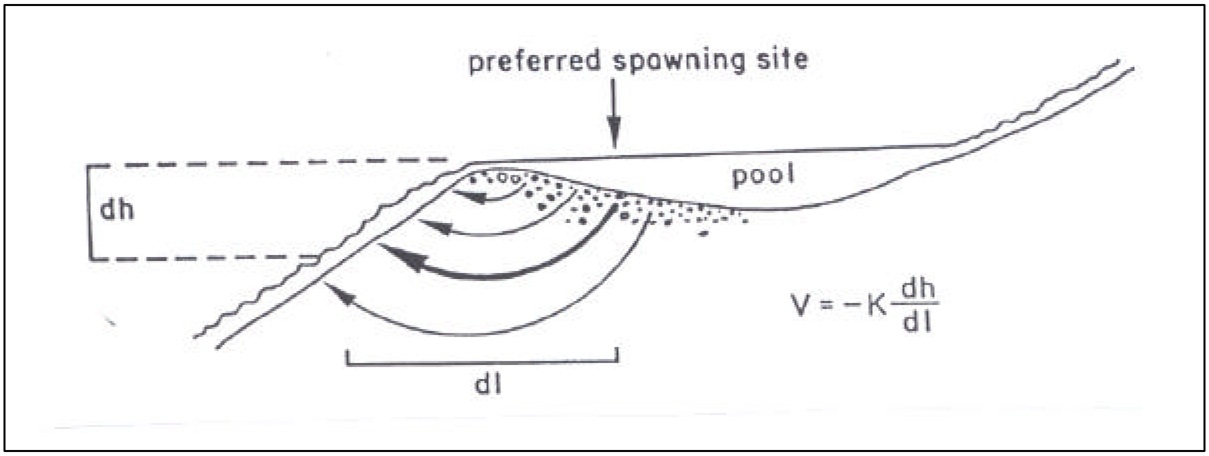

Figure 10. Flow through a gravel bed as determined by Darcy’s law (Source: Kondolf 2000).

Emergence

Successful emergence requires connected pore space through which the alevins can pass. Field and laboratory studies have demonstrated that, in some gravels, eggs may incubate successfully, alevins hatch and live in the intragravel environment, but alevins cannot migrate upward to the surface because fine sediment blocks intragravel pore spaces (e.g., Hawke 1978, Phillips et al. 1975). The sediment sizes held responsible for blocking emergence are typically between 1 and 10 mm (Bjornn 1969, Phillips et al. 1975, Harshbarger and Porter 1982), while those blamed for reducing permeability are finer than 1 mm (0.4 in) (McNeil and Ahnell 1964, Cederholm and Salo 1979, Tagart 1984). Thus, emergence requirements set another limit to interstitial fine sediment, but of a coarser caliber than those of concern for incubation.

Laboratory and field researchers have attempted to relate fine sediment content to incubation and emergence success, producing a wide range of results (Table 2). In a comprehensive and influential review, Chapman (1988) suggested that this variability resulted from a lack of understanding the structure of the egg pocket (the small area within the redd containing the eggs), and argued for intensive studies of egg pockets. While such studies would no doubt prove helpful in better understanding processes within the redd, the study results might have only limited direct application to the common problem of evaluating the suitability of potential spawning gravels because, by definition, no egg pockets yet exist to be sampled. In a thoughtful comment, Young et al. (1990) noted that variations in female fecundity and egg viability can affect the results of relations between egg survival and gravel size.

Table 2. Fine Sediment Standards for 50% Survival in Lab and Field Studies of Salmonid Eggs (Kondolf and Wolman 1993)

		Maximum Percentage of Grains Finer Than				
Reference or Statistic	Species [a]	0.83 mm	2.0mm	3.35mm	6.35 mm	9.5mm
Hausle and Cobe (1976)	Brook Trout		10			
Weaver and White (1985)	Bull Trout					16, 40
Bjornn (1969)	Chinook salmon				15,26	
Tappel and Bjornn (1983)	Chinook salmon				40	
McCuddin (1977)	Chinook salmon				30,35	
Koski (1975, 1981)	Chum salmon			27		
Cederholm and Salo (1979)	Coho salmon	7.5, 17				
Koski (1966)	Coho salmon	21		30		
Phillips et al. (1975)	Coho salmon			36		
Tagart (1984)	Coho salmon	11				
Irving and Bjornn (1984)	Cutthroat trout				20	
Irving and Bjornn (1984)	Kokanee				33	
Irving and Bjornn (1984)	Rainbow Trout				30	
NCASI (1984)	Rainbow Trout	12			40	
Bjornn (1969)	Steelhead				25	
Tappel and Bjornn (1983)	Steelhead				39	
McCuddin (1977)	Steelhead				27	
Phillips et al. (1975)	Steelhead			25		
Mean		13.7	10.0	29.5	30.3	28.0
SD		4.7	0.0	4.2	7.4	12.0

[a] Scientific names: brook trout *Salevlinus fontinalis*; bull trout *S. confluentus*; chinook salmon *Oncorhynchus tshawytscha*; chum salmon *O. keta*; coho salmon *O. kisutch*; cutthroat trout *O. clarki*; kokanee *O. nerka*; rainbow trout (nonanadromous) and steelhead (anadromous) *O. mykiss*

Juvenile Rearing and Intra-Cobble Habitat

To avoid predation in the first few days after emerging from the gravel, fry continue to use protected habitats such as the interstices of gravel and cobble beds. After a few days, fry begin swimming close to the channel banks using cover provided by woody debris and overhanging vegetation where available. Fry survival and growth will further be affected by factors such as the density of fry, predators, streamside vegetation and canopy, and quantity and quality of benthic food (Sandercock 1991). Benthic food productivity is also dependent on the availability of quality intra-gravel and intra-cobble habitat.

Fluvial Gravels as Sources of Construction Aggregate

Sand and gravel deposited by fluvial processes 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 terraces, or by in-channel (instream) mining, removing sand and gravel directly from river beds with heavy equipment.

Fluvial and Glacial Outwash Deposits

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 (Dunne et al. 1981, Barksdale 1991). Sand and gravel are commercially mined from the active channel (instream mining) and from floodplain and terrace pits (Figure 11). Instream gravels thus require less processing than many other sources, are easily worked by heavy equipment, 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 commonly of sufficiently high quality to be classified as "PCC-grade" aggregate, suitable for use in production of Portland Cement concrete (Barksdale 1991).

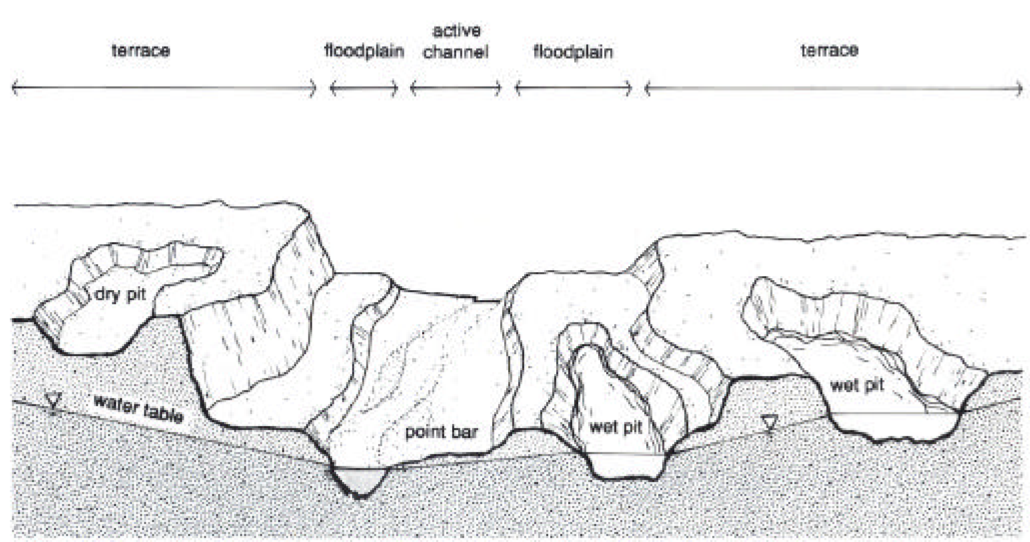

Figure 11. Alluvial deposits exploited for aggregate depicted in relation to river channel morphology and alluvial water table (Source: Kondolf 1994).

River channels and floodplains are important sources of aggregate in many settings by virtue of the durability of river-worked gravels and their sorting by fluvial processes. The relative importance of alluvial aggregates is a function of the quality, location, and processing requirements of alluvial aggregates, and the availability of alternative sources in a given region. Of the 120 million tones (132 million short tons) of construction aggregate produced annually in California (Carillo et al. 1990, Tepordei 1992) virtually all is derived from alluvial deposits. Annual aggregate production from alluvial deposits in California exceeds estimated annual average production of sand and gravel by erosion in the entire state by an order of magnitude (Kondolf 1995). In Washington State, however, riverine sources account for less than 17 percent of the state's production (Collins 1995) thanks to the availability of extensive glacial outwash deposits convenient to many markets, especially in the Puget Sound region (Leighton 1919, Lingley and Manson 1992). Kroft (1972) and Dunne et al. (1981) mapped the distribution of glacial deltas along the Snoqualmie, Cedar, and Green Rivers. Dave Knoblach (WDNR) is presently mapping potential gravel sources, including glacial outwash deposits, at 1:100,000 scale (D. Norman, WDNR, personal communication 2000). Maintaining these supplies into the future will depend, in part, on protecting outwash deposits from being rendered inaccessible by urban development.

Other sources can supply suitable aggregates for most purposes, although more processing may be required.

Other Potential Aggregate Sources

Reservoir Deltas

Reservoir sediments are a largely unexploited source of building materials in the US. In general, reservoirs deposits will be attractive sources of aggregates to the extent that they are sorted by size. The depositional pattern within a reservoir of gravel, sand, silt and clay 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 (1.4 mi) Shikma Reservoir is mined in its upper 600 m (1970 ft) to produce sand and gravel for construction aggregate, and in its lower 1 km (0.6 mi) 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 insuring continued deposition of sand and gravel in the upstream portion of the reservoir, silt and clay in the downstream portion (Figure 12). 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).

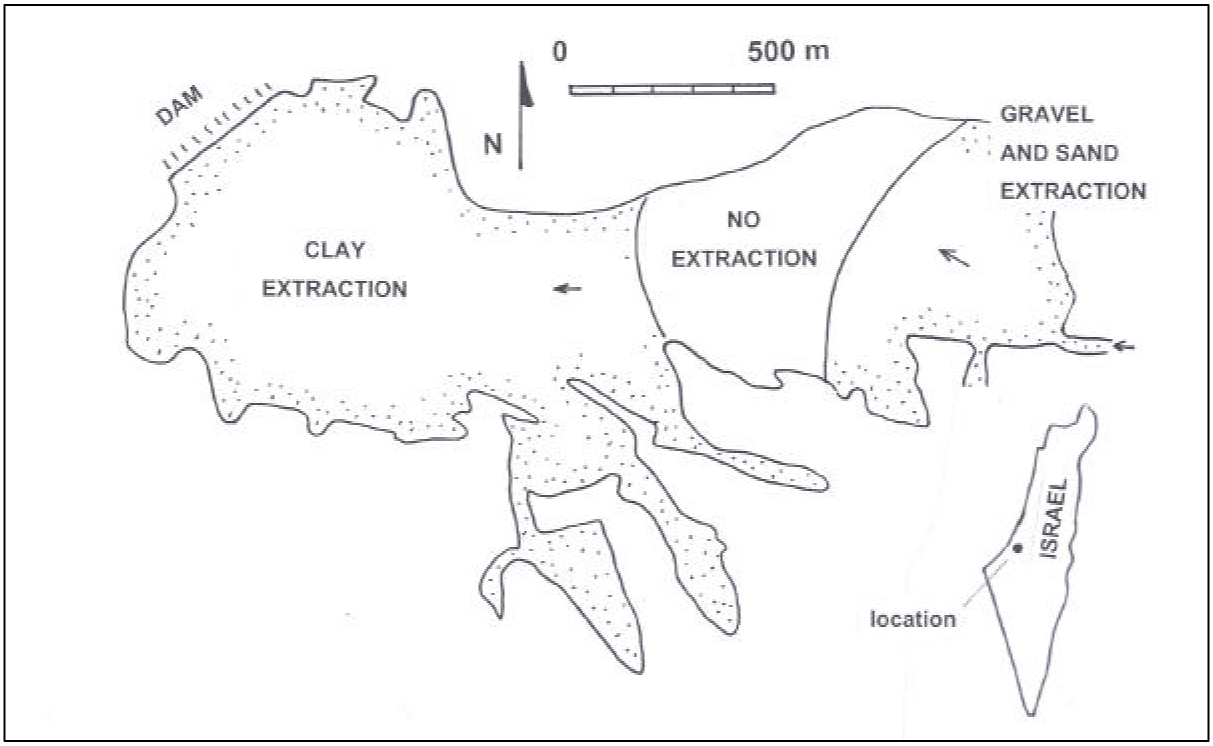

Figure 12. Distribution of sediment and extraction zones in Shikma Reservoir, Israel (Adapted from Laronne 1995).

Extraction of reservoir deposits serves to restore some (albeit a small fraction) of the reservoir capacity lost to sedimentation. Replacing lost capacity through new reservoir construction is expensive, especially since the most favorable reservoir sites have already been developed. The cost of new reservoir construction (estimated from projects proposed or under construction on the Carmel and Santa Ana rivers in California) is approximately US\$ 2.50 m^{-3} (\$3000/acre-foot), and the cost of mechanical removal of sediment can exceed US\$200 m^{-3} (\$20,000/acre-foot), based on costs in Sierra Nevada hydroelectric diversion dams (Kondolf 1995). The economic value of avoiding further reservoir capacity loss could be a significant factor making removal 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 US, 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. Many reservoir deltas are relatively inaccessible or distant from markets, such that transportation costs make their exploitation uneconomical under present conditions. Wetlands may form in reservoir delta deposits, posing potential conflicts with regulations protecting wetlands. The likely opposition of nearby residents to gravel-truck traffic would be another obstacle to development of these resources.

Dredging sediment from reservoirs for reinjection downstream has been suggested as a solution to sediment starvation below dams. Largely due to cost, this practice has not been reported. On the Rhine, gravels mined from floodplain pits are injected into the channel below the downstream-most dam, Iffezheim (Kuhl 1992).

Dredger Tailings

Dredger tailings are long linear deposits left by historical gold mining operations. The tailings are stratified: sand and silt are overlain by mounds of clean gravel and cobble, which hold no interstitial water and thus support little vegetation. These inert ridges of gravel and cobble cover large areas of floodplains of rivers in former gold-mining areas in California. Dredger tailings are mined and the site reclaimed to recreation and wildlife habitat on the American River northeast of Sacramento (Figure 13), and have been used to fill and/or isolate abandoned gravel floodplain gravel pits along the Tuolumne River.

Recycled Concrete Rubble

Recycling concrete rubble is another potentially important source of aggregate, especially in urban areas, where suitable rubble is likely to be most available and transport distances may be less than for virgin aggregate (Burke et al. 1992). Recycling concrete rubble not only avoids environmental impacts of new aggregate production, but avoids impacts of disposing the rubble as well. Rubble requires crushing and removal of any steel rebar present, but steel rebar can be extracted for scrap and the operator receives a fee for accepting the rubble from the waste generator (e.g., Sonoma County 1993). As far as aggregate quality is concerned, nearly half of current aggregate uses could be met with recycled concrete (Bairagi et al. 1993), thanks in part to equipment available to process concrete rubble (Hillmann 1991). But use of recycled concrete is limited by supply and economic considerations under present regulatory regimes. About 3% of aggregate demand is met by recycled concrete in France, more in Holland (with over 40 recycling plants) and Denmark (Poulin and Martin, 1998)

Figure 13. Dredger tailings, Mississippi Bar, American River, California (Photo by Kondolf 1990).

a) Prior to gravel extraction, cobble mounds remain unvegetated due to lack of retained moisture. b) after gravel mining, sterile mounds of cobbles have been removed and the land resculpted.

Aggregate Extraction Methods

Instream Gravel Mining

Instream gravel mining has been conducted using a variety of techniques, though some of these are no longer used in Washington State due to their impacts on fish habitat.

Bar Scalping

Bar scalping (or "skimming") is extraction of gravel from the surface of gravel bars. Historical scalping commonly removed most of the gravel bar above the low flow water level, leaving an irregular topography (Figure 14). Current permit conditions generally require that surface irregularities be smoothed out and that the extracted material be limited to what could be taken above an imaginary line sloping upwards and away from the water from a specified level above the river's water surface at the time of extraction (typically 0.3-0.6 m (1-2 ft)). Fish and wildlife agencies in California and Washington typically require that the bar, which originally would typically have a steep margin and relatively flat top, be left after scalping with a smooth slope upwards from the edge of the low water channel at a 2 percent gradient (Collins 1995) to avoid stranding fish in shallow holes after high flows that inundate the bar (Figure 15). Bar scalping is commonly repeated year after year. To maintain the hydraulic control provided to upstream by the riffle head, the preferred method of bar scalping is now generally to leave the top one-third (approximately) of the bar undisturbed, mining only from the downstream two-thirds.

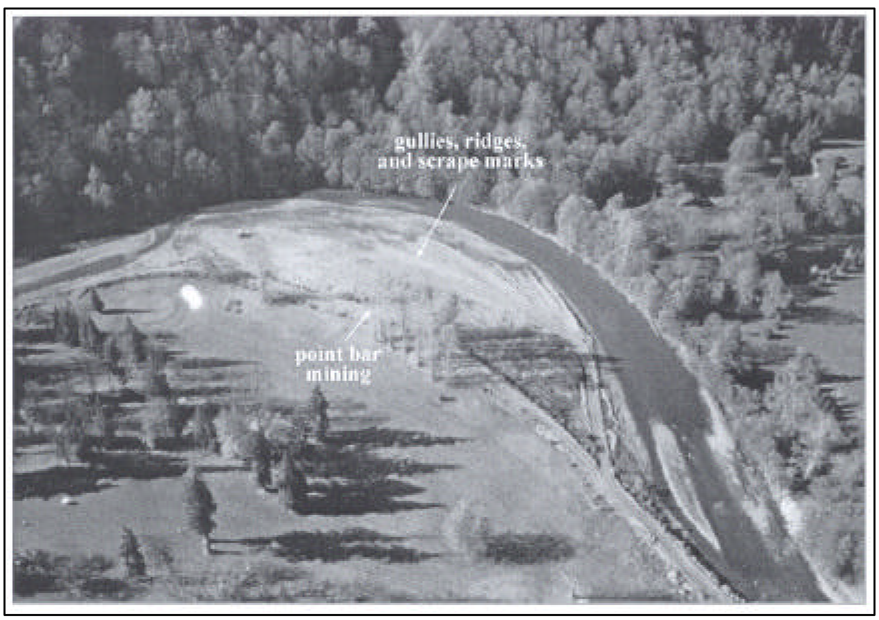

Figure 14. Oblique aerial view of freshly scalped point bar in the Wynoochee River, ca. appx 1965 (Photograph by Lloyd Phinny, Washington Dept. of Fisheries, reproduced from Norman et al. 1998, used by permission).

Figure 15. Experimental bar scalping, Fraser River, British Columbia (Photo by Laura Rempel, March 2000).

Dry-Pit Channel Mining

Dry-pit channel mines are pits excavated within the active channel on dry intermittent or ephemeral stream beds with conventional bulldozers, scrapers and loaders (Figure 16). Dry pits are often left with abrupt upstream margins, from which headcuts are likely to propagate upstream.

Figure 16. Dry pit excavation, Stony Creek, California (Photo by Kondolf July 1990).

Wet-Pit Channel Mining

Wet-pit mining involves excavation of a pit in the active channel below the surface water in a perennial stream or below the alluvial groundwater table, requiring the use of a dragline or hydraulic excavator to extract gravel from below the water surface. Trenches, linear instream pits, have been excavated as an alternative to other forms of instream extraction, and for a period in the early 1990s were recommended in California as potentially creating pool habitats missing from channels.

Bar Excavation

A pit is excavated at the downstream end of the bar as a source of aggregate and as a site to trap gravel. Upon completion, the pit may be connected to the channel at its downstream end to provide side channel habitat. On the Russian River, California, recent proposals for bar mining include leaving the bar margins untouched and excavating from the interior of the downstream part of the bar, but above the water surface elevation, a variant intermediate between bar scalping and bar excavation.

Instream Gravel Traps

Sand or "bedload traps" have been used to reduce sand in downstream channels for habitat enhancement in Michigan and elsewhere (e.g. Hubbs et al. 1932). Such traps can also be potential sources of commercial aggregate, provided the amounts so collected are sufficient to be economically exploited. One advantage of gravel traps as a method for harvesting gravel is the concentration of mining impacts at one site, where heavy equipment can remove gravel without impacting riparian vegetation or natural channel features. Gravel can be removed year after year from the bedload trap. An idealized gravel trap shown in Figure 17 has short dikes to create a constriction downstream and to hold the resultant higher stages. Gravel is removed from the downstream end of the deposit, and a grade control structure at the upstream end of the gravel trap prevents headcutting upstream from the extraction. There is no hydraulic impact upstream due to the extraction, because the engineered constriction is the hydraulic control during high flows. The concentrated flow scours a deep pool immediately downstream from the constriction, which may be important habitat in aggrading reaches where pool formation is limited by deposition (Bates 1987). Such a bedload trap in Hansen Creek at Northern State Hospital (4.8 km (3 mi) northeast of Sedro Woolley) was installed upstream of a bridge constriction to reduce bedload sediment loading downstream. The Hansen Creek pit was situated so that bedrock outcrops in the channel bed immediately upstream would prevent headcutting, obviating without the need for engineered grade control structures.

As discussed in the case study below, three gravel traps have been excavated in the Big Quilcene River annually since 1995 in exposed gravel bars, and have completely filled with gravel during the first high flows each year, except for the 2001 water year (due to a lack of high flows). Historical channel bed aggradation has been a management concern on the lower Big Quilcene River. Collins (1993) compared cross-section surveys to estimate that the thalweg had aggraded an average of about 61 cm (2 ft) between 1971 and 1993, equivalent to a sedimentation rate of approximately 460 m^3/km/y (1,000 cubic yards/mile/year). Previous management has included gravel extraction and bar scalping amounting to approximately 2950 cubic meters/km/year (2,400 cubic yards/mile/year), substantially reducing the potential bed aggradation rate. However, gravel extraction and bar scalping have disrupted the available spawning habitat, increased turbidity and spawning gravel sedimentation, and made riffles wider and shallower, making fish passage more difficult (Williams et al. 1995). The gravel traps are excavated in favorable sites away from the low flow channel, and have yielded an average of about 1,500 m^3/y (2,000 yd^3/y).

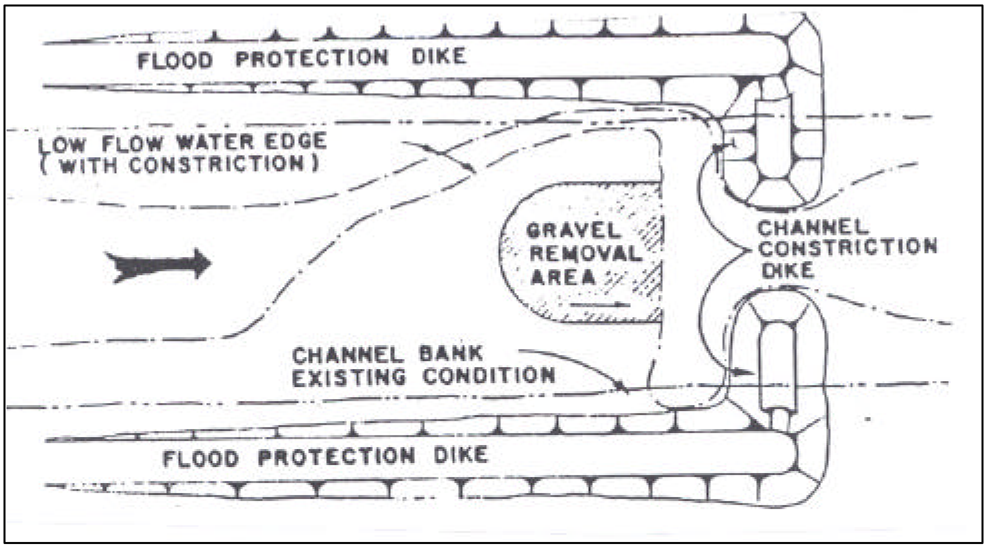

Figure 17. Idealized gravel trap (Source: Bates 1987).

Channel-wide Instream Mining

In rivers with a highly variable flow regime, gravel is commonly extracted across the entire active channel during the dry season. The bed is evened out and uniformly (or nearly so) lowered. Cache Creek in California provided a visually impressive example of channel-wide mining, prior to this type of mining being prohibited by the county, with the entire active channel excavated over a width of 460 m (1500 ft), creating a broad, flat surface that was likened to an airport by local residents (Figure 18). This method has not been used in Washington State for about two decades, due to concerns over its habitat impacts (Norman et al. 1998).

Floodplain and Terrace Pit Mining

Another important method of gravel mining is the excavation of pits on the current floodplain or adjacent river terraces (Figure 11). If located on higher terraces, these pits may be above the water table (dry pits) and are excavated with graders and scrapers. More commonly, however, floodplain pits intersect the water table and are wet pits, at least part of the year. Floodplain pits are excavated dry (with excavators, front-end loaders, etc.) if the pit is (and can be) dewatered by pumping water out (Figure 19). Generally this implies that the gravel contains enough interstitial fine sediment that the rate of groundwater inflow is not too high to be handled by pumps, or that stream flow is low enough (at least seasonally) that inflowing groundwater can be handled by the pumps. The Beech Street Pit along the Yakima River in Yakima was excavated to depth of more than 30 m (100 ft), separated from the river channel by only a narrow levee (Norman et al.1998). Groundwater inflowing from seeps along the pit walls was collected in ponds at the base of the pit, then pumped up to the level of the floodplain, where it was put in a canal that discharged to the river downstream. The pit filled with water after mine closure. If the water cannot be kept out during the period of active mining, the pit is wet and may be mined with a clamshell dredge on a dragline, a less efficient technique (Figure 20).

An important characteristic of floodplain pits is their distance from the current channel. Many floodplain pits are up to five times as deep as the adjacent river (Norman et al. 1998), some deeper (e.g. the Beech Street Pit in Yakima). Pits are often dug adjacent to the active channel because cleaner, better sorted gravels (with less overbank sediment as overburden) may be available there. Pits adjacent to current channel are frequently separated from the channel by riprap berms. In Washington State, floodplain pits behind berms have typically been excavated to a depth of 5-15 m (16-50 ft), but since approximately 1985, increasingly pits have been authorized to depths of 20-30 m (65-100 ft) (Collins 1995).

The relation of a typical dragline-excavated floodplain gravel pit to an actively meandering river is shown in Figure 21, from Norman et al. (1998).

Processing plants to sort gravels and wash fine sediments from them are often set up next to floodplain pits. The fine sediments are usually retained in a “fines” pond from which water is allowed to seep into the floodplain. In addition, concrete batch plants and/or “hot” asphalt plants are often located adjacent to floodplain pits to take advantage of the convenient source of aggregate and because the floodplain sites are often sufficiently far removed from human settlement to avoid noise complaints.

Floodplain pits are increasingly dug as alternatives to in-channel mining, and many are later reclaimed (with varying degrees of success) to wildlife habitat. However, the purpose of the pits was to provide construction aggregate not habitat enhancement.

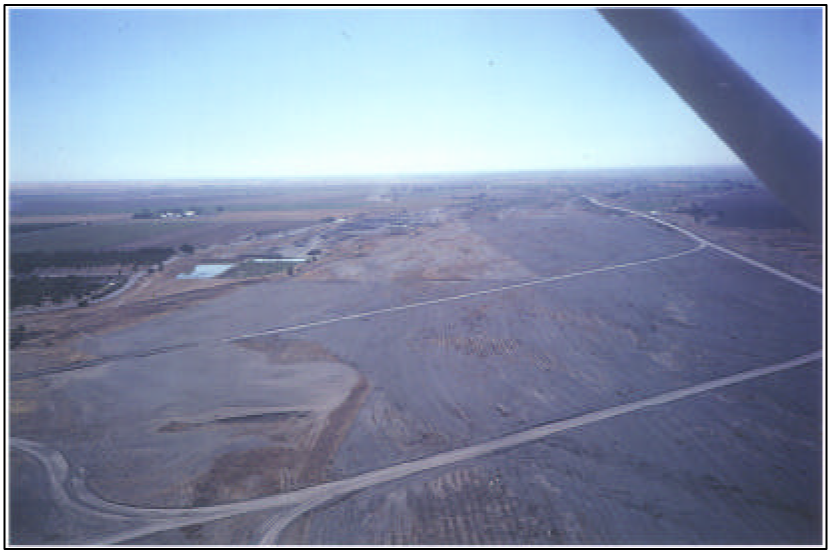

Figure 18. Oblique aerial view of the channel of Cache Creek, August 1994 (Photograph by Kondolf 1994).

Channel form was obliterated by gravel mining, leaving a vast, flat, scraped surface with haul roads running across the channel bed. Channel-wide instream mining is no longer practiced on Cache Creek, with extraction occurring in pits separated from the currently active channel by berms.

Figure 19. Gravel pit dewatered by pumping, Alameda Creek at Sunol, California (Photo by Kondolf 1990).

Figure 20. Wet pit on Wynoochee River being excavated by dragline (Photo by Kondolf 1994).

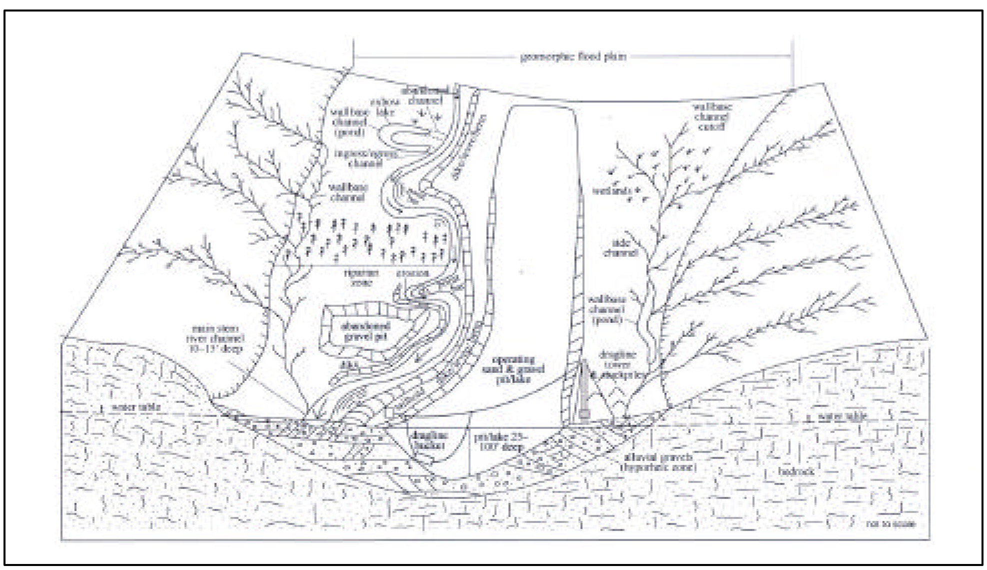

Figure 21. Diagram of a typical dragline-excavated floodplain gravel pit, showing the scale of pits relative to the channel and the narrow dike separating pit from the active channel (Reproduced from Norman et al. 1998, used by permission).

Also shown are floodplain water bodies such as side channels and wall base channels.

Extent of Aggregate Mining Along Washington State Rivers

In-channel Mining

Collins (1995) estimated the extent of in-channel mining in Washington State since 1970 from WDNR Aquatic Lands Division royalty records, Hydraulic Project approvals, and Shoreline Permit records. Collins emphasized that no single agency had records of all in-channel mines, and that data on production rates was very limited. He identified twenty rivers with in-channel extraction for commercial or flood control purposes from 1970-1991, and provided a rough estimate (± 30%) of statewide annual average production of 5-10 x 10^5 m^3/y (6.5-13 x 10^5 yd^3/y) (Table 3). Most instream mines in Washington State are located in western Washington (Collins 1995, Norman et al. 1998) (Figure 22).

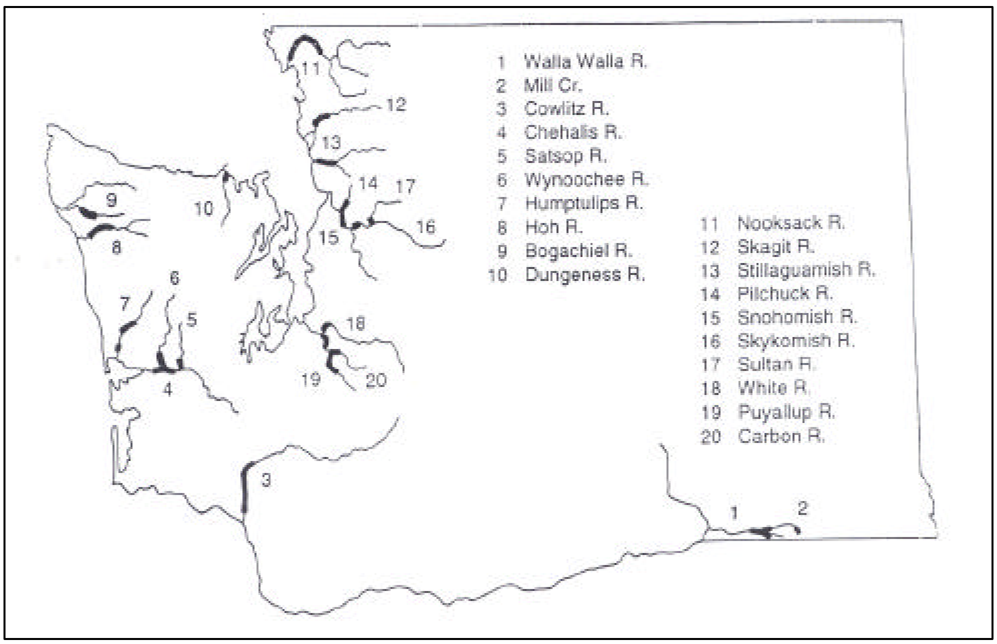

Figure 22. Distribution of in-channel mining sites in Washington State (Source: Collins 1995).

In-channel mining was formerly more widespread in Washington. Its extent has been reduced principally in response to increased concern about environmental effects, primarily on salmonid habitat. Floodplain mines have been substituted for instream mines in many reaches.

Dredging for navigational purposes in freshwater environments is undertaken by the Army Corps of Engineers along the Columbia and Snake Rivers at a number of locations from the Pacific Ocean to the Washington-Idaho border. Freshwater navigational dredging has also been undertaken on the Cedar River, the Cowlitz River (downstream of Mt St Helens), and probably

Table 3. List of rivers with in-channel gravel bar mines in Washington State since 1970 (reproduced from Collins 1995)

River and County	Location (river kilometer)	Years and Amount
Bogachiel (Clallam and Jefferson)	16-33	Contracts with WDNR at various times between 1965 and 1991.[1]
Carbon (Pierce)	0-2 and 9-11	386,675 m^3 removed 1974-1985 by Pierce County and Inter-County River Improvement (30, 723 m^3/yr average.)[2]
Chehalis (Grays Harbor)	9-29	Contracts with WDNR at various times 1950-1982.[1]
Cowlitz (Lewis and Cowlitz)	10-55	Contracts with WDNR at various times 1934-1985.[1]
Dungeness (Clallam)	3-14	WDOE permits 1992-1997.[2]
Hoh (Jefferson)	8-40	Contracts with WDNR at various times between 1961 and 1986.[1]
Humptulips (Grays Harbor)	4-9 and 26-45	Estimated 30,000 m^3/yr to 70,000 m^3/yr in 1950-1985.[4]
Mill Creek (Walla Walla)	4-6 and 30-32	About 9,000 m^3/yr permitted by WDOE 1986-1994.[2]
Nooksack (Whatcom)	2-33	Contracts with WDNR from 1961-1995.[1] Current WDOE permits for extraction of 526,000 m^3/yr.[3] Average removal 1960-1993 49,000 m^3/yr, 1990-1993 average 147,000 m^3/yr.[5]
Pilchuck (Snohomish)	2-11	35,000 m^3/yr removed in 1969-1972, and 11,000 m^3/yr in 1972-1991.[6]
Puyallup (Pierce)	17-40	637,393 m^3 removed 1974-1985 by Pierce County and Inter-County River Improvement (53,116 m^3/yr average).[2]
Satsop (Grays Harbor)	2-6	Rough estimate of 15,000 m^3/yr removed from 1950s to 1985.[4]
Skagit (Skagit)	21-43	Contracts with WDNR at various times 1949-1993.[1]
Skykomish (Snohomish)	5	Removal of 38,000 m^3/yr in 1961-1969, 11,000 m^3/yr in 1969-1976, and 7,600-11,000 m^3/yr in 1977-1978.[7]
Snohomish (Snohomish)	27 22	km 27: Removal of 1,500-2,300 m^3/yr in 1952-1978.[7] km 22: Removal of 3,800-4,600 m^3/yr from at least 1962 to 1991.[6]
Stillaguamish (Snohomish)	6-28	Removal 1965-1985 averaged 41,000 m^3/yr. 1985-1991 averaged 103,000 m^3/yr.[8]
Sultan (Snohomish)	0-1	Removal 1968-1978 ranged 380-2,800 m^3/yr and averaged 1,100 m^3/yr.[9]
Walla Walla (Walla Walla)	42-59	About 50,000 m^3/yr permitted by WDOE 1986-1994.[2]
White (Pierce)	5-19	596,000 m^3 removed 1974-1985 by Pierce County and Inter-County River Improvement (50,000 m^3/yr average).[2]
Wynoochee (Grays Harbor)	3-24	Ranged from 7,600-46,000 m^3/yr from at least 1960s to 1985.[4] 3,800 m^3/yr since 1985.[3]

Sources: [1] WDNR Division of Aquatic Lands records. [2] Prych (1988). [3] WDOE Shoreline permits. [4] Survey of mining operators reported in Collins and Dunne (1986). [5] KCM (1994). [6] Survey of mining operators reported in Collins (1991). [7] Dunne (1978). [8] Survey of mining operators reported in Collins (1993). [9] Snohomish County PUD No. 1 (1984).

elsewhere in the state, though we encountered no compilation of dredging locations and rates. The Marine Dredging Issues White Paper compiled by Si Simenstad, Barbara Nightengale, and Lauren Mark documents the extent of dredging in marine environments.

Floodplain Mines

Collins (1995) also mapped the distribution of mines larger than 1.2 ha (93 acres) that intersected the water table in active floodplains in the state (Table 4, Figure 23). (Floodplain mines smaller than 1.2 ha are not regulated by the state Surface Mined Land Reclamation Act.) Two thirds of floodplain mines (larger than 1.2 ha) in the state (by area) are along the Yakima River and its major tributaries, the Naches and Cle Elum Rivers. There are numerous large commercial floodplain gravel pits along lower reaches of the rivers, and more than a hundred smaller, shallower gravel pits throughout the basin – approximately one floodplain pit per river kilometer. Seventeen percent of floodplain mines are situated along the Chehalis River and its major tributaries in Southwest Washington. The remaining 19 percent are situated along the Cowlitz and East Fork Lewis Rivers in southern Washington, and the Stillaguamish, Pilchuck, and Skykomish Rivers along the western Cascades. Some portion of these "floodplain" mines may actually have been located in terraces, and thus are less likely to be captured by the channel.

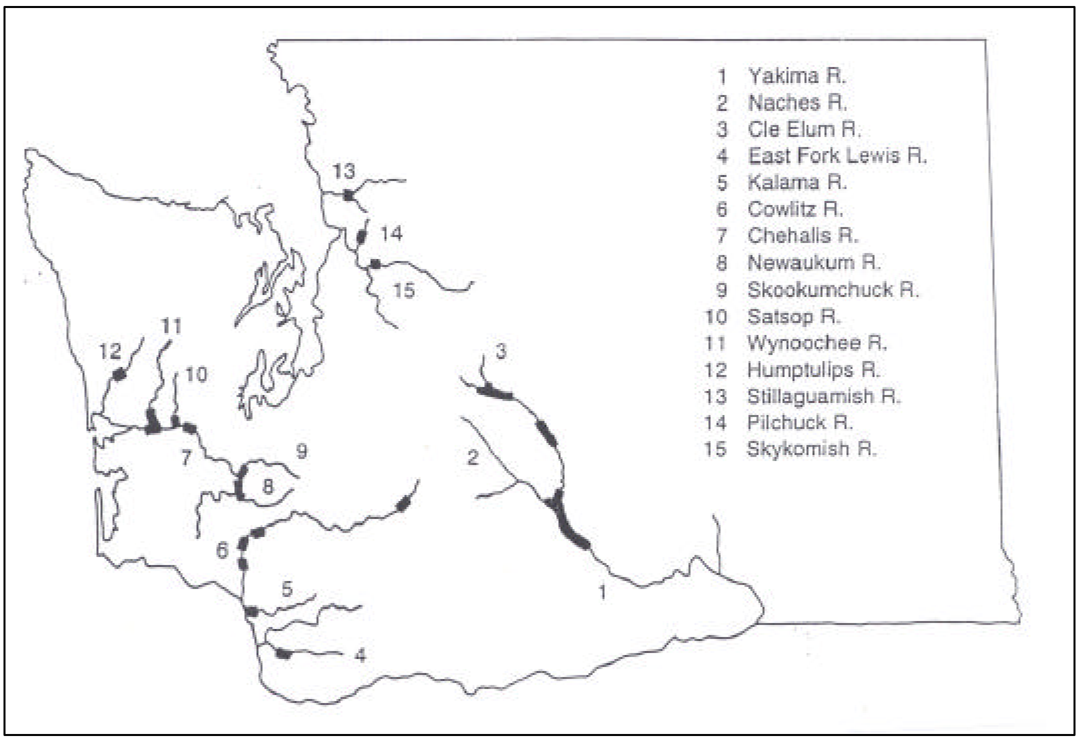

Figure 23. Distribution of floodplain mining sites in Washington State (Source: Collins 1995).

Table 4. List of floodplain mine pits in Washington State (reproduced from Collins 1995). Only pits or clusters of pits >1.2 ha and deeper than groundwater table included.

River Basin[1]	River Kilometer[2]	Area (ha)[3]	Number of Lakes	Percent of Total (by area)
Yakima River				
Lower River -	4, 21, 123	18	8	2
Zillah Reach (1986)	132-171	111	27	12
Selah-Moxee Valleys (1986)	173-195	187	36	21
Ellensburg Reach (1986)	238-258	168	44	19
Cle Elum Reach -	286-337	53	22	6
Naches River -	0-9	34	9	4
Cle Elum River -	1-2	7	6	1
Yakima River Basin Total		**578**	**152**	**64**
Chehalis River				
Lower Chehalis River (1988-1993)	17-49	68	21	8
Upper Chehalis River -	108	9	1	1
Wynoochee River (1988-1992)	0-17	28	13	3
Satsop River (1991)	2, EF 13	9	4	1
Skookumchuck River (1990-1992)	0-8	27	9	3
Newaukum River -	1-2	9	2	1
Chehalis River Basin Total		**150**	**50**	**17**
Cowlitz River				
Castle Rock Reach -	29	3	1	<1
Toledo Reach (1990)	45-59	51	16	2
Packwood Reach (1990)	202	4	1	<1
East Fork Lewis River (1990)	13-14	40	10	4
Kalama River (1990)	3	17	8	2
Pilchuck River (1991)	8-10	16	4	2
Humptulips River -	39-43	5	3	1
Skykomish River (1992)	5	33	1	4
Stillaguamish River(1991)	25	3	1	<1
Other River Basins		**172**	**45**	**19**
State Total		**900**	**247**	**100**

1 For reaches with active mining, year is given of most recent aerial photo or map information consulted to measure lake areas.
2 River kilometers are from river miles indicated on 1:24,000 scale topographic maps.
3 Area measures as of date indicated in column 1 in cases where mining may be ongoing.

Effects of Instream Aggregate Mining

While aggregate mining along rivers involves many of the same transient impacts as upland quarries (noise, dust, traffic, and contaminant spills), of more fundamental concern are the environmental effects that are unique to the dynamic riverine environment and that have no counterpart in upland quarries. By removing sediment from the active channel bed, instream mines interrupt the continuity of sediment transport through the river system, disrupting the sediment mass balance in the river downstream and inducing channel adjustments (usually incision) extending considerable distances (commonly 1 km (0.6 mi) or more) beyond the mine site itself (Figure 24). Instream gravel mining directly alters the channel geometry and bed elevation and may involve extensive clearing of vegetation, flow diversion, sediment stockpiling, and excavation of deep pits (Sandecki 1989). Regardless of the mining technique, the pre-existing channel morphology is disrupted and a local sediment deficit is produced. Excavating trenches or pits in the gravel bed also leaves a headcut on the upstream end of the extraction. Other effects of instream mining include reduced loading of coarse woody debris in the channel, which is important as cover for fish (Bisson et al. 1987).

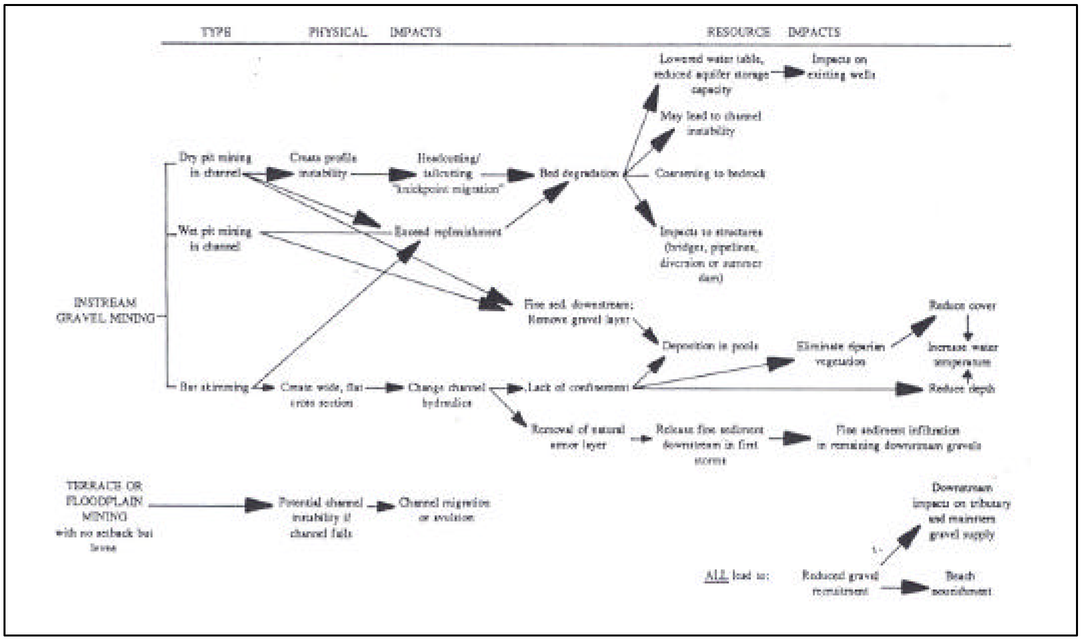

Figure 24. Flow chart summarizing impacts of gravel mining (Source: Kondolf and Matthews 1993).

Until recently, these effects unique to riverine extraction were largely unrecognized. For example, in reporting on the quality and quantity of aggregates available in Arizona (all described as alluvial deposits), Keith (1969) made no mention of possible environmental impacts of their extraction. In a recent comprehensive review volume on aggregates published by the Geological Society of London, the section on "Environmental Considerations" discussed only noise, dust, blasting, nuisance, visual impact, and restoration (Smith and Collins 1993:95-97).

Elsewhere in the volume, the section on "Fluvial deposits" included a paragraph noting that instream mining "may change the dynamic equilibrium of a river: it may improve land drainage but increase scouring and erosion of the channel, as well as cause damage to bridge abutments" (Smith and Collins 1993:16-17). However, there was no treatment of the topic beyond this brief paragraph.

The form and dimensions of alluvial river channels are largely functions of the discharge (amount and distribution on a seasonal and inter-annual basis) and sediment load (amount, caliber, and temporal distribution) supplied from the basin (Leopold et al. 1964). See Miller et al.'s (2001) white paper on Channel Design for a discussion of channel form issues. By directly altering the channel geometry and elevation, instream mining induces channel adjustments. Moreover, by harvesting the river's bedload, mining disrupts the sediment mass balance of the river. From geomorphic principles, we would predict that this change in independent variables should induce a channel response, and along many rivers the channel has been observed to erode its bed and banks.

In most rivers experiencing instream mining, there are other human influences that could conceivably induce similar channel responses, such as upstream dam construction, bank protection and flood control works, or increased peak runoff from land use changes in the catchment. However, attributing these impacts (at least partially) to instream gravel mining is often justified because of the scale of extraction relative to bedload sediment supply: extraction commonly exceeds supply, in many cases by an order of magnitude or more (e.g., Collins and Dunne 1989, Kondolf and Swanson 1993, Kondolf 1995).

As the effects of aggregate extraction from river channels on channel form, physical habitat, and food webs become increasingly recognized and understood, instream aggregate extraction has received increased scrutiny, especially in salmon-bearing rivers and streams.

Transient Effects of Site Operations

Aggregate mining operations in rivers have a number of transient impacts in common with upland quarries, such as noise, traffic, dust and other emissions, and potential spills of diesel fuel or other contaminants. Along large rivers, the mines may be located some distance from settlement, so noise and dust may generate less public opposition than if they occurred closer to upland settlements. However, some of these transient impacts can be considered more serious when they occur on a river, because of sensitive aquatic species present, and because of the role of water in transporting contaminants to sensitive receptors. For example, spills of hazardous materials may be more serious because of the exposure of aquatic organisms and potential contamination of water supplies. Similarly, the noise of gravel extraction and processing operations may affect holding, feeding, or migratory behavior of fish, although this topic has not been directly addressed in the scientific literature.

During the period of mine operation, noise, truck traffic, and clearing of riparian vegetation can be expected to affect holding, feeding, or migratory behavior of fish and other biota in the riparian corridor. Similarly, for the period of mine operation and over a subsequent period of recovery, the processing facilities (usually located on the floodplain) displace former uses, typically riparian habitat or agriculture.

Extraction from the channel within the water suspends fine sediment, usually at times of year when high concentrations do not normally occur and when the river is unable to disperse the suspended sediments (Weigand 1991). Fines washed from gravels may not be completely contained in fines settling pits, and may contribute fine sediments to the channel chronically or episodically during floods or failure of retaining walls. Often an old gravel pit is used as a pit to settle fines. Once filled with fine sediments, the former pits act as fine sediment plugs in the floodplain. Subsequent channel migration can erode these, releasing concentrated fine sediments into the channel.

Extraction directly destroys any invertebrates or other organisms that do not escape from the mine site (Starnes 1983, Thomas 1985). More extensive impacts result from propagation of effects offsite, notably from turbidity and siltation of the downstream channel, which can reduce the abundance (and change composition of) macroinvertebrate populations and induce a change in fish populations (at the site and within several kilometers downstream) from more desirable species to those tolerant of high suspended sediment concentrations (Cordone and Kelly 1961, Forshage and Carter 1973, Rivier and Seguier 1985). On the South Fork Chehalis River, Ziebell (1957) documented a 98% decrease in invertebrates immediately downstream of the discharge of a gravel washing operation, with populations returning to upstream levels 10.5 km (6.5 mi) downstream. Similar results were reported below gravel washing operations on the Wynoochee River (Zeibell and Knox 1957) and on the Truckee River, California (Cordone and Pennoyer 1960). Such direct discharges of wash water are generally controlled today, but it may be impossible to completely prevent some increased fine sediment load and turbidity below gravel extractions.

Bar Scalping Effects

Because the extraction depths are limited, extraction rates from scalping operations may be lower than those associated with deeper extractions, and there is a common perception that the effects are less. However, the available evidence suggests that substantial impacts result from bar scalping. Gravel bar scalping typically reduces preferred salmonid spawning and rearing habitat by removing riparian vegetation and woody debris, reducing the area of adjacent pools and riffles, and causing channel bed degradation upstream and downstream (Collins 1995).

By disrupting the pavement (the active coarse surface layer of a gravel bed channel) (Parker and Klingeman 1982), bar scalping can make the gravel bed more mobile at lower flows than formerly. This increased bed mobility increases the potential to scour salmon redds. Moreover, without the coarse surface layer, interstitial fine sediments can be mobilized by small freshets, which may lack the duration needed to disperse the fine sediments downstream, but may simply re-deposit them a short distance downstream.

By removing most of the gravel bar above the water level, the confinement of the low water channel is reduced or eliminated, changing the patterns of flow and sediment transport through the reach. One potential effect is reduced efficiency of sediment transport through the newly-unconfined reach, triggering channel instability due to resulting coarse sediment deposition and inducing fine sediment deposition on the channel bed. Bar scalping has the potential to cause the channel to take a steeper path across the inside of the bar, or meander cut-off (Dunne et al. 1981). As a scalped bar rebuilds over time through deposition, it is less stable than a mature bar and thus redds constructed in it may be more prone to scour (Dunne et al. 1981).

Just as the upstream end of submerged riffles serve as hydraulic controls for upstream pools at low flow, the upstream end of bars serve as controls for upstream reaches at bankfull flow (see Leopold et al. 1964 for discussion of bankfull flow). At high flow, channel roughness can depend primarily on channel forms such as bends and bars, in contrast to low flows, where skin friction may be more important. Thus, removal of the bar may alter channel hydraulics upstream as well as at the mined site itself. To date, the only study documenting this effect is that of Pauley et al. (1989), who documented scour in riffles upstream of a skimmed bar on the Puyallup River, Washington, apparently because of reach-scale channel steepening associated with the lowering of the downstream hydraulic control. This potential effect has raised concerns in Washington because of the potential loss of incubating salmon embryos in the scoured gravels (Bates 1987).

The current channel may be abandoned and a former channel adopted instead following bar skimming or bar removal (Dunne et al. 1981). Bar scalping has also been shown to eliminate side channels, which are important habitats for juvenile salmonids (Pauley et al. 1989, Weigand 1991). Bar scalping on the Puyallup, Carbon, and White rivers from 1987 to 1988 reduced mean side-channel riffle habitat area from 1130 to 780m^2 (1350-930 yd^2) and mean side-channel glide and pool habitat area from 1290 to 0m^2 (1550-0 yd^2) at treatment sites while these habitat areas increased or remained unchanged at control sites (Weigand 1991). The same study demonstrated that side-channel habitats were preferred by 0+ coho salmon and 0+ mountain whitefish. For example, 88% of all coho salmon sampled in the Puyallup River and 73% of all coho salmon sampled in the Carbon River were captured by electrofishing side-channel pool habitats (which typically form at the downstream end of bars). All of these side-channel pool habitats were eliminated by channel changes during high flows following bar scalping, while side-channel pool habitats at control sites on the same rivers were generally unaffected. These data and other observations supported the hypothesis that an observed reduction in recreational fisheries on the Puyallup, Carbon, and White Rivers was primarily due to effects of channelization and scalping (e.g., Don Finney, personal communication, MIT, Auburn, Washington *as cited in* Weigand 1991).

Even if riparian vegetation is not removed from the scalped bar itself, riparian vegetation is typically removed to provide access to the removal site, reducing riparian cover and shading

(Weigand 1991). Also, large organic debris on bar surface is removed during bar scalping, reducing the potential for salmonid habitat creation as the debris would have been transported through the system during future high flows.

A little-recognized effect of gravel bar scalping is the potential for increased establishment of willows on skimmed gravel bars in western North America and other semiarid regions where moisture availability during the growing season normally limits plant survival. Where undisturbed gravel bars are more than 1 m (3 ft) above the low water elevation of the river, the bars may remain largely unvegetated because seedlings that establish there are likely to die from desiccation by virtue of the depth to water table during the dry summer and fall. By lowering the top of the bar, bar scalping may create shallow water table conditions in which the willows can establish (Figure 25). Establishment of vegetation on the bar may create habitat, although of one type, pioneer woody riparian (less valuable for salmonids than complex channel features such as undercut banks), while eliminating open bar habitat. Moreover, like the vegetation that encroaches downstream of dams, it may reduce the flood capacity of the channel and limit mobility of the bar, potentially altering flow paths. Even if woody riparian vegetation establishes on scalped bars, a net loss of habitat is likely to result from bar scalping when the full range of effects is taken into account.

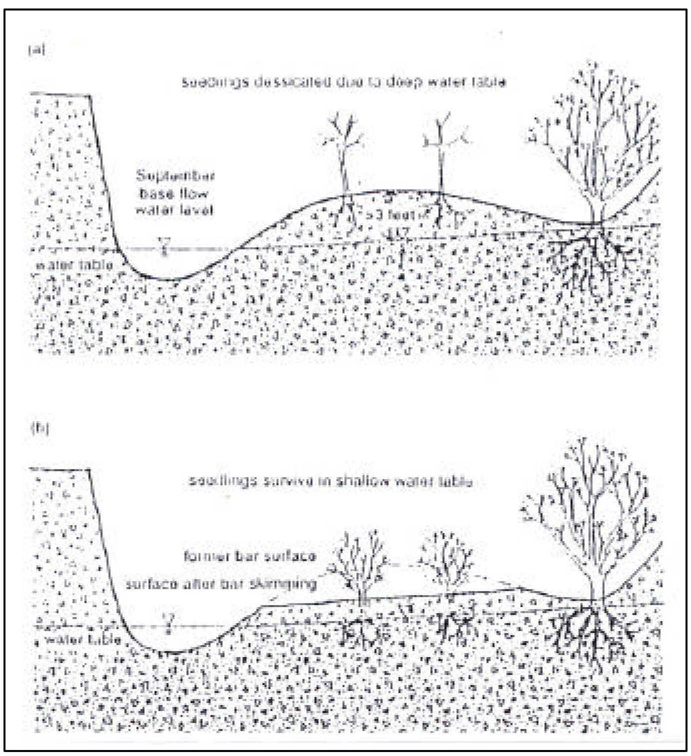

Figure 25. Diagram showing potential effect of gravel bar scalping on establishment of willow seedlings (Source: Kondolf 1998).

a) Top of the unscalped gravel bar is too high for willow establishment because the depth to ground water is too great. b) After scalping, the surface of the gravel bar is closer to the water table, permitting survival of the seedlings.

Bar scalping can also induce channel instability, as described by Dunne et al. (1981:92):

> "…not all of the bedload transport occurs over the portion of a bar that emerges from the water and can be scalped in summer. Harvesting of all or most of the bedload passing a site would interrupt the supply to downstream bars and diminish or even eliminate them. Channel banks would be undermined in new locations, the river could shift unpredictably, and damage would probably occur to structures and to spawning areas. For this reason, gravel harvesting should be conducted in such a way that a considerable fraction of the bedload arriving at a site is allowed to pass on to downstream bars."

To maintain sediment transport continuity, Dunne et al. (1981) recommend approving extraction rates that are less than the amount estimated to be transported to the site from upstream on an annual average basis. Recognizing the large variability in annual sediment transport (actual sediment transport to the site in any given year is typically much less than or much more than the annual average rate), and site-specific considerations, Dunne et al. (1981) further recommended analysis of sequential aerial photographs to measure channel change induced by past extraction and intervening floods, and an adaptive management approach to refine allowable extraction rates.

Effects of Channel-wide and Instream Pit Extraction

Channel-wide excavation results in complete loss of channel complexity and low flow channel confinement. Flow spreads out shallowly over the flat bed, too shallow to provide habitat for most salmonids. The wide shallow flow, devoid of shading from vegetation, maximizes exposure to the sun and heats up rapidly, potentially driving water temperatures out the range of tolerance for salmonids. (In extreme cases, such as Cache Creek, California, shown in Figure 18, natural bed features such as bars are eliminated over the entire channel width.) Rates of this type of mining are often high, commonly exceeding replenishment rates, and thereby inducing sediment-starvation and its attendant problems of incision, etc.

Excavation of pits in the active channel alters the equilibrium profile of the streambed, creating a locally steeper gradient upon entering the pit (Figure 26). This over-steepened knickpoint (with its increased stream power) commonly erodes upstream in a process known as headcutting. 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 26). Thus, instream pit mining commonly results in incision both up- and downstream of the pit, albeit through different mechanisms.

Trenching has effects similar to other forms of instream pit mining. By lowering the thalweg more per unit of gravel extracted, trenching probably exacerbates thalweg incision more than other forms of instream mining at comparable rates, increasing the threat of undermining infrastructure and exacerbating effects of lowered water tables. After a period in the early 1990s when they were recommended by wildlife agencies, trenches fell out of favor in California because of the geomorphic effects of trenching, and because the habitat benefits anticipated from trenching did not materialize, with the "pools" created by trenching not necessarily of suitable size and shape to provide good salmonid habitat.

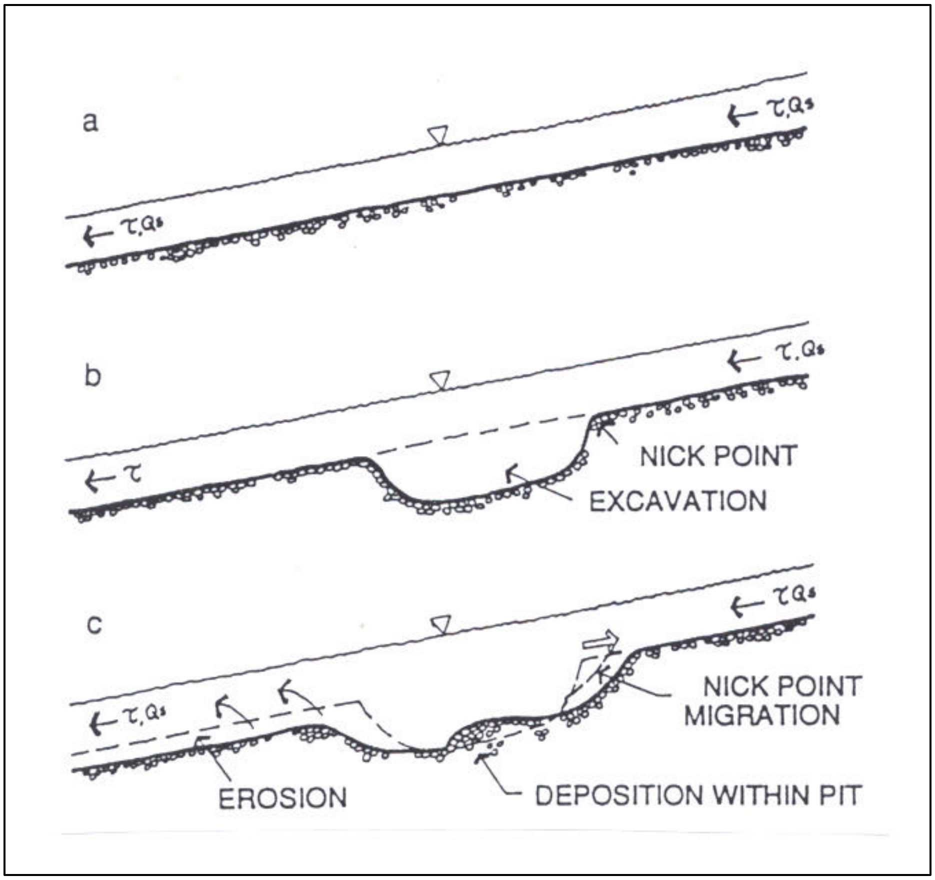

Figure 26. Incision produced by instream gravel mining (Reprinted from Kondolf 1994, used with permission of Elsevier Science-NL).

a) The initial, p reextraction condition, in which the river's sediment load (Q_s) and the sheer stress (ô) 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 (ô) but no sediment load. c) The nickpoint migrates upstream, and hungry water erodes the bed downstream, causing incision upstream and downstream.

Effect on Sediment Budget

Instream mining results in removal of mass (gravel) from the reach, thereby lowering the average elevation, and in that sense making future deposition more likely. Even using environmentally preferred extraction techniques from bars, leaving the head of the bar and in some cases the stream margin in place, and lowering the interior of the downstream part of the bar surface, mining creates a site for deposition of gravel and sand. Thus, at a minimum bar scalping represents a loss term in the sediment budget. Because

> "…bars are temporary storage sites through which sand and gravel pass, most bars are in approximate equilibrium so that the influx and downstream transport of material are equal when averaged over a number of years. If all of the sand and gravel reaching such a bar is removed, the supply to bars downstream will diminish. Since sand and gravel will continue to be transported from these downstream bars by the river, their size will decrease." (Dunne et al. 1981:89)

The magnitude of this impact basically depends on the magnitude of the extraction relative to bedload sediment supply and transport through the reach. Annual gravel bar harvesting rates have exceeded the replenishment rates for the last few decades on the Humptulips, Wynoochee, and Satsop Rivers. Erosion from the bed has made up the difference in volume. Gauge and cross-section data indicate that the beds in reaches of each river with intensive gravel extraction have been lowering at the rate of 30 mm/yr (0.1 ft/yr) (Collins and Dunne 1986). As described below, incision can reduce overbank flooding, increase in-channel shear stress and sediment transport potential, destabilize bed and banks, lower the alluvial water table, and change the distribution and structure of riparian vegetation.

Downstream Coastal Sediment Effects

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 "under nourished", 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).

The supply of sediment to beaches has been reduced from many rivers by a combination of instream sand and gravel mining, and dams (which both trap sediment and reduce the magnitude of flows needed to transport the sediment downstream) (Jenkins et al. 1988). Downstream coastal effects of sediment starvation from dams and gravel mining have been documented in many environments, including Tuscany, Corsica (Gaillot and Piégay 1999), Australia (Erskine 1988), and California (Inman 1985, Brownlie and Taylor 1981), and the Elwha and Columbia Rivers.

Along the southern California coast, discrete littoral cells with sediment sources (river mouths) and sinks (offshore canyons) can be distinguished. The Oceanside littoral cell near San Diego receives sediment from Santa Margarita, San Luis Rey, and San Dieguito Rivers, and San Mateo and San Juan Creeks, estimated under natural conditions at 209,000 m^3/yr (273,000 yd^3/yr), roughly balancing the longshore transport rate of 194,000 m^3/yr (254,000 yd^3/yr) and the loss into the La Jolla submarine canyon of 200,000 m^3/yr (262,000 yd^3/yr) (Figure 27) (Inman 1985). Sediment supplied from all these rivers has been reduced by gravel mining and dams. Bedload supply from the San Luis Rey River was reduced about 6 million tonnes (6.6 million short tons) from 1935 to 1975 by Henshaw Dam (Brownlie and Taylor 1981) and further by extensive sand and gravel mining in the reach between the dam and the river mouth. To compensate for reduced riverine sand supplies, "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 maintenance of coastal beaches into the existing legal framework, a system of “sand rights”, analogous to water rights, has been proposed in California (Stone and Kaufman 1985).

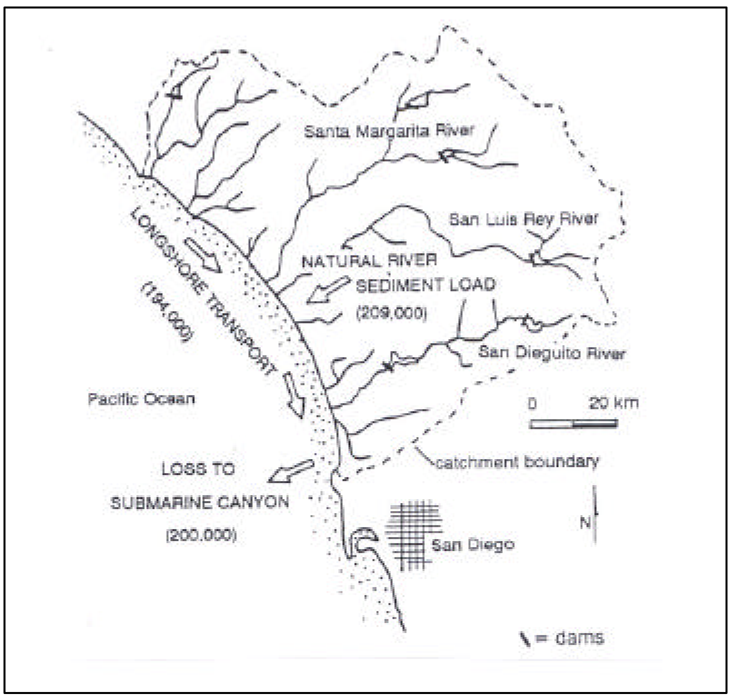

Figure 27. The Oceanside Littoral Cell, showing sediment supply from rivers, longshore transport, and loss to the La Jolla submarine canyon (Adapted from Inman 1985, used by permission).

Along the coast of Washington and Oregon at the mouth of the Columbia River, accelerated beach erosion has been documented, resulting from the cumulative effects of upstream dams and navigational dredging, as discussed below under Navigational Dredging.

Channel Incision

By removing sediment from the channel, disrupting the preexisting balance between sediment supply and transporting capacity, and in some cases creating a locally steeper gradient upon entering the pit, instream gravel mining typically induces incision upstream and downstream of the extraction site (Sandecki 1989). The over-steepened knickpoint (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 et al. 1990), and up tributaries sometimes several kilometers, such as in the case of Dry Creek, a tributary to the Russian River in northern California (Harvey and Schumm 1987). As headcuts migrate upstream, incision propagates upstream.

An unusually clear example of mining-induced knickpoint migration appears on a detailed topographic map prepared from photogrammetric 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 (4600 ft) downstream of Capay Bridge, where the miner left a 4 m (13 ft) high headwall on the upstream edge of the excavation. After the 1992 winter flows, a knickpoint over 3 m (10 ft) deep extended 700 m (2296 ft) upstream from the upstream edge of the pit (Figure 28). After the flows of 1993, the knickpoint had migrated another 260 m (850 ft) upstream of the excavation (not shown), and in the 50-yr flood of 1995, the knickpoint migrated under the Capay Bridge, contributing to the near-failure of the structure (Northwest Hydraulics Consultants 1995).

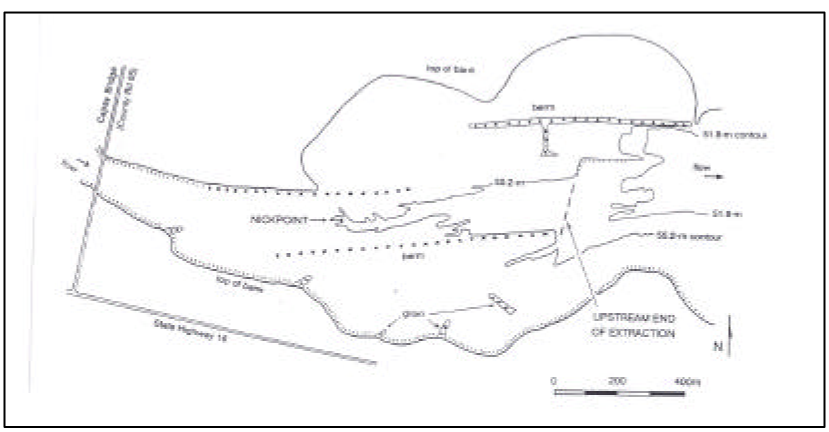

Figure 28. Knickpoint upstream of 4-m-deep gravel pit in the bed of Cache Creek, California, as appearing on a topographic map of Cache Creek prepared from fall 1992 aerial photographs (Source: Kondolf 1997).

Original map scale 1:2400. Contour interval 0.6 m.

Just as below dams, below instream gravel mines gravel-bed rivers may become armored (i.e., coarsened), limiting further incision (Dietrich et al. 1989), but eliminating salmonid spawning habitat. (Here the term "armoring" refers to development of a coarse surface layer on the bed, not protection of banks with rock revetment.)

Incision has been documented on a wide range of rivers around the world. Many of the published examples are from California (Table 5), but include examples in Europe and Australasia (Table 6). We found relatively little documented data on incision rates in Washington state (Table 7). Among the best quantifications of incision in Washington State was that developed for the Humptulips, Wynoochee, and Satsop Rivers by Collins and Dunne (1986). Annual average sediment supply was exceeded after about 1960 on all three rivers, and comparison of contemporary and historical bed elevation data from bridges and stream gauges showed an average incision rates of approximately 30.5 mm/yr (0.1 ft/yr) on the river reaches subjected to intensive gravel mining. Likewise, on the Pilchuck River, 40 km (25 mi) north of Seattle, Collins (1991) documented 0.5 m (1.5 ft) average channel bed degradation from 1972 to 1991 over a 11 km-long (6.9 mi) reach beginning about 0.6 km (0.4 mi) upstream from the river mouth (Table 7). Maximum local bed degradation was 2 m (7 ft), with increased degradation located downstream from the two largest in-channel pits.

The specific effects of gravel-mine-induced incision described in the following paragraphs are mostly negative, but we note that in cases where the channel is otherwise aggrading (naturally or due to land-use changes), gravel mining can be used to reduce or reverse aggradation and thereby reduce channel stability, as discussed below.

Channel Instability

Instream mining can cause channel instability both up-and downstream 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 knickpoint migrates upstream, its incision and bank undercutting release additional sediment to downstream reaches, where the channel may aggrade and thereby become unstable, as observed by Sear and Archer (1995) on the Wooler Water, UK. Incision in the mainstem Russian River propagated up its tributary Dry Creek, resulting in undercutting of banks, channel widening (increasing from 10 to 400 m (33-1300 ft) in places), and destabilization, increasing delivery of sand and gravel to the mainstem Russian River (Harvey and Schumm 1987).

Infrastructure Damage

Direct effects of incision include undermining of bridge piers (e.g. Bull and Scott 1974, Parsons Brinckerhoff Gore & Scott, 1994, Kondolf and Swanson 1993, Mossa and Autin, 1998) and other structures, and exposure of buried pipeline crossings and water supply facilities (Lehre et al. 1993, Marcus 1992). The downstream margin of the Kaoping Bridge on the Kaoping River, Taiwan, was protected with gabions, massive coastal concrete jacks, and lengthened piers

Table 5. Examples of Mining-Induced Incision in California

Stream	Description	Reference
Blackwood Creek	Upstream and downstream incision and a four-fold increase in sediment delivery to Lake Tahoe between 1960 and 1983 caused by pit capture.	Todd, 1989
Cache Creek	average 4.6m, maximum 8.2m, from 1959-1980	Collins and Dunne 1990, Northwest Hydraulics, 1995
Clear Creek	average >0.9 m under the bridge built in 1950.; incision occurred 1971-1987	Kondolf and Matthews, 1993 based on review of bridge records of the California Department of Transportation
Cottonwood Creek	average 2.4 - 3m, maximum >4.3m, from 1964-1986	"
Dibble Creek	average 1.5 - 1.8m, maximum 2.1m, from 1965-1980. Bridge built in 1948	"
Dry Creek	3.2m of upstream progressing incision between 1940 and 1984 attributed to lowered base level in mainstem Russian River (to which Dry Creek is tributary) from intensive aggregate mining, to a lesser extent to aggregate mining in Lower Dry Creek.	Harvey and Schumm, 1987
Dry Creek	average 1.5m, maximum 2.4m, under the bridge from 1955-1986. Bridge built 1954; rock dam built in 1980	Kondolf and Matthews, 1993 based on review of bridge records of the California Department of Transportation
East Sand Slough	average >1.8m, from 1947-1987. bridge built in 1965; rock dam built 1982	"
Etna Creek	average 1.2m, maximum 2.4m, under the bridge 1959-1987	"
Frasier Creek	average 1.8m, maximum 2.4m, from 1954-1980	"
Merced River	average 1.8m, maximum 2.4m, from 1953-1972.	"
Putah Creek	average 2.4m, maximum 4.6m, under the bridge 1954-1982. bridge built in 1954; heavy rock placed several times.	"
Russian River	average 3.5m, maximum 5.5m, below Healdsburg Dam, deep pit mining 1950-60, bar skimming 1960-1990	Collins and Dunne 1990
Sacramento River	Loss of spawning gravels for Chinook salmon between 1942 and 1980 as a result of gravel extraction for construction of Shasta Dam (5.5 million m^3) and subsequent urban demand, along with trapping of bedload by the dam.	Parfitt and Buer, 1980
San Benito River	3m incision along 7.5 km from 1952-1995	Harvey and Smith 1998
San Juan Creek	9m induced by a 17m-deep in-channel pit downstream	Simons et al., 1979
San Luis River	2.4-3.7m near Hwy 395 bridge, incision (unknown amount) over a 22 km reach	Sandecki and Avila 1997
San Simeon Creek	average 1.5m, maximum 4.6m, under the bridge at San Simeon Creek Road, 1966-1991	Matthews and Associates 1991
Santa Clara River	average 4.8m, maximum 6.2m, from 1957-1978. partial failure 1979, foundations lowered from 1969	Simons, Li and Association. 1983
Santa Ysabel Creek	average >3m, from 1968-1980	CalTrans bridge records
Stony Creek	5 m below Hwy 32 bridge from 1975-1990	Kondolf and Swanson, 1993
Sulphur Creek	average 1.2 - 1.5m, maximum 2.1m, from 1964-1980. Bridge built in 1948 and washed out in 1963; rebuilt in 1964, rock check dam installed 1980	Kondolf and Matthews, 1993 based on review of bridge records, California Department of Transportation
Thomes Creek	average 1.2 m under the bridge 1965-1975	"
Tujunga Wash	scour averaging 4.3 m over a 914 m reach upstream of gravel pit	Scott 1973

Table 6. Examples of Mining-Induced Incision Elsewhere

Stream	Description	Reference
Hunter River, Australia	Annual extraction of 200,000 tonnes downstream of Glenbawn Dam was predicted to cause incision.	Erskine et al. 1985
Mamquam River, British Columbia	Up to 2m over a 1km reach from 1981-1983 resulting from annual extraction of about 140,000 m^3.	Sutek Services, Ltd. 1989
Manawatu R., New Zealand	1m average at stream gauge near Palmerston North from 1952-1976	Page and Heerdegen 1985
McKenzie River, Oregon	2m over 26 years resulting from gravel mining and the decay of a wooden irrigation sill	Williamson et al. 1995
Mississippi River, Mississippi	Selective mining for aggregate caused percentage of gravel in bed to decrease from 26% to 4% between 1968 and 1972, with presumed effects on river morphology.	Lagasse and Simons 1976
Mogami,Omono, and Yoneshiro Rivers, Japan	Up to 1.5m from 1960-1968. Net volume of bed material removed by incision "nearly corresponds to the total quantity of gravel mining."	Sato 1971
Otaki River, New Zealand	Riverbed lowered exposing base of river control works.	Soil and Water 1985
Oyodo River, Japan	Up to1.4 m in the Upper Oyodo from 1955-1969 attributed to sand and gravel mining. Up to 2.7m in the Lower Oyodo attributed principally to sand and ravel mining from the channel, also to construction of "sand catch dams" upstream.	Sato 1975
River Tchaja, Bulgaria	5m caused by annual extraction of 300,000-400,000 m^3, inducing undercutting of banks, loss of farm land, and threatening a high-tension line.	Kostourkov 1972
South Platte River, Colorado	1.2m between 1983 and 1986 induced by an in-channel pit and a captured off-channel pit downstream	Stevens et al. 1990
Unidentified, Tucson, Arizona	4m under a bridge from 1965-1973, evidently as a result of instream gravel mining	Bull and Scott 1974
Wooler Water, England	Up to 9m over a 2km reach from 1966 to 1995 resulting from extraction of over 750,000 m^3 of gravel between 1920 and 1980.	Sear and Arches 1998
Yasu River, Japan	Extraction of 1.7 million m^3 was associated with loss of 2.9 million m^3 to incision and bank erosion, 1958-1962.	Kira 1972

Table 7. Examples of Mining-Induced Incision in Washington

Stream	Description	Reference
Pilchuck River	0.5m average and 2.1m maximum over 12km reach from 1972-1991	Collins 1991
White River Washington	0.6m average over 11 km reach, from 1974-1984	Prych 1988
Wynoochee, Satsop, and Humptulips Rivers	0.5m average incision between 1950 and 1980 on each of 3 rivers studied caused by annual extractions of "several tens of thousands" of m^3 in excess of supply.	Collins and Dunne, 1986

(Figure 29), but headcutting of over 7 m (23 ft) from an instream gravel mine downstream finally caused the bridge to fail in September 2000 (Figure 30). An even more dramatic example of undermining occurred on the Douro River below the confluence of the Douro and Tamega Rivers in Portugal near Porto in March 2001. Both the Douro and the Tamega are dammed directly upstream of the confluence, and a gravel mine operates 5 km (3 mi) downstream. Thus, the confluence reach is starved of upstream gravel supply and subject to regressive erosion from the gravel mine downstream. Prolonged high flows in the 2001 winter progressively downcut the bed until one pier of the bridge toppled. Unfortunately, the bridge failed just as a bus passed, plunging 70 people to their deaths (www.elpais.es/multimedia/internacional/puente.htm). A commission of inquiry established after the tragedy concluded that inadequate regulation of sand and gravel mining, along with failure of the responsible agency to act on evidence of progressive bed degradation, was responsible for the disaster (Correia et al. 2001). However, the commission focused on the specific situation in the Douro and did not recognize such sediment starvation from dams and gravel mining as a systematic problem throughout Portugal.

Figure 29. 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 Kondolf, October 1995).

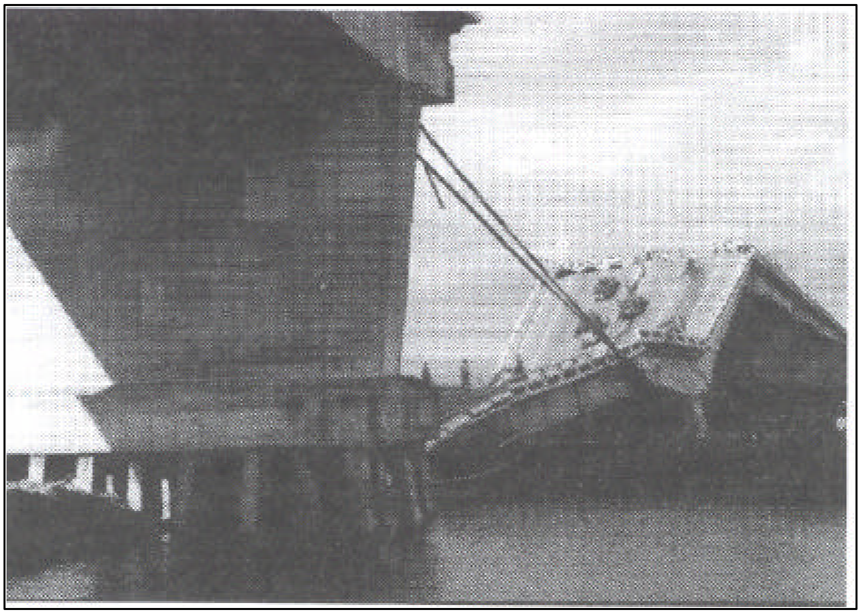

Figure 30. Failure of the Kaoping Bridge from gravel mining.

Even in less dramatic cases, undermining of bridges by mining-related incision can have serious consequences. Harvey and Smith (1998) documented channel incision and consequent widening along the San Benito River, California, and calculated the costs of infrastructure damage directly attributable to gravel mining from 1952 to 1995. Three bridges, a siphon, and utility crossing were damaged due to gravel mining at a total infrastructure damage cost of about $11 million, equivalent to about $3/ton of gravel produced. Such calculations have not been made for most rivers with gravel mining impacts, but it is likely that comparable values would be found elsewhere. For example, Collins (1991) documented undermining of a bridge and exposure of a water supply pipeline from instream mining on the Pilchuck River. The infrastructure costs are borne by the taxpayers at large and thus represent a substantial public subsidy to the industry.

Groundwater Effects

Incision typically lowers the alluvial water table, because the channel (a constant head boundary) determines the level down to which the alluvial groundwater drains (Galay 1983, Mas-Pla et al. 1999). As the channel lowers, the alluvial water table migrates downward as well. The water table lowering will extend farther from the channel in highly permeable alluvium such as gravel and sand, a short distance in finer grained alluvium with lower permeability. Alluvial aquifers with finer grained alluvium that receive substantial recharge from valley sides and tributaries may maintain a water table that slopes steeply toward the channel despite incision (Creuzé des Châtelliers and Reygrobellet 1990).

Lowering of the alluvial water table results directly in loss of groundwater storage. In some cases, wells can be lowered and water pumped from greater depths, increasing water costs significantly. Along the lower Drôme River, a formerly braided reach in the 19th century, an estimated 6 x 10^6 m^3 (7.8 x 10^6 yd^3) of groundwater storage has been lost because of incision of 3-5 m (10-16 ft) since 1960. In this case, it is not possible to simply lower wells, because the alluvial gravels had been dewatered down to the molassic bedrock (SOGREAH, 1991). Along the Enza River, Italy, an estimated 1.4 x 10^6 m^3 (1.8 x 10^6 yd^3) of groundwater storage was lost in 25 years due to incision (Tagliavini 1978). The Lake County (California) Planning Department (1992) estimated that incision from instream mining in small river valleys could reduce alluvial aquifer storage from 1 to 16 percent, depending on local geology and aquifer geometry.

Lowering of the alluvial water table can induce profound ecological and landscape changes, including loss of hyporheic habitat as adjacent banks are dewatered (Creuzé des Châtelliers and Reygrobellet 1990). More widely documented has been the loss of riparian vegetation (or prevention of seedlings from establishing) as the water table drops below the root zone of riparian plants (e.g., Reilly and Johnson 1982, DeBano and Schmidt 1989). Scott et al. (1995) documented die-off of cottonwoods from mining-induced incision along a Colorado stream.

Another potential effect of reduced alluvial groundwater storage is reduced summer baseflow due to reduced contributions to the stream from the adjacent alluvial aquifer in which groundwater storage has been reduced. This effect is particularly strong for incised channels in coarse grained alluvium with high permeability. In a finer grained alluvial aquifer supplied by upland sources, water table gradient to an incised channel will be greater, potentially increasing groundwater flow to the channel. Reduced baseflow contributions during critical low-flow periods may stress salmonid populations or cause fish kills due to reduced low-flow habitat and increased water temperatures. Reduced baseflow may lower water quality by reducing the effect of dilution. In general, channel incision changes the pattern of groundwater-surface flow interactions in alluvial streams, including the extent and flux of groundwater upwelling zones that provide important habitat for fish and benthic invertebrates and regulate stream temperature (Ward and Stanford 1995). Hyporheic groundwater upwelling zones have also been shown to provide spawning habitat preferred by fall chinook salmon in large rivers, such as the Columbia River in Washington State (Geist 2000).

Bed Coarsening and Fining

Concurrent with incision may be coarsening of bed material and direct loss of gravels used for spawning by salmonids (Kondolf and Matthews 1993). Bed coarsening can increase the median grain size available in former spawning areas above the suitable spawning size threshold (Figure 9) for the local salmonid population. This has been documented on the Sacramento River below Shasta and Keswick Dams, resulting from the combination of sediment starvation by upstream dams and intensive mining (including complete removal of a gravel bar of 765,000 m^3 (1 million yd^3) for aggregate for Shasta Dam) (Parfitt and Buer 1980). Matthews (1991) documented bed coarsening on San Simeon Creek, California, as a result of gravel mining.

Bed fining is also possible if the fines left over from screening gravel are released into the channel. On the Stanislaus River, California, Kondolf et al. (2001) documented increased sand content in the bed from 1994-2000, evidently from scour of fine sediments from the bottom of instream gravel pits. Collins (1991) observed potential channel bed armoring in the lower 2 miles of the Pilchuck River, 40 km (25 mi) north of Seattle, as a result of reach-scale incision.

Hyporheic Zone Effects

Thanks to the history of post-glacial sea level rise, many river channels are underlain by deposits of sand and gravel many times deeper and wider than the active river channel. These deposits form aquifers that exchange groundwater with surface water in the adjacent river channel. The portion of these riverine deposits that contains alluvial groundwater that is recharged by surface flow or discharges to surface flow is termed the hyporheic zone. The hyporheic zone influences surface water temperature and quality by direct exchange, buffering variations in surface water conditions. Benthic invertebrates also use the hyporheic zone as habitat and refugia, commonly migrating tens or even hundreds of meters away from the channel bed into the surrounding hyporheic zone. Small fish have also been observed using hyporheic zones as refugia. The transmissivity or permeability of sand and gravel comprising the hyporheic zone varies in vertical, lateral, and longitudinal dimensions, leading to complex interactions between alluvial groundwater and surface water. The simplest exchange between surface and groundwater is illustrated in Figure 10, which shows surface flow enter the channel bed at the top of the riffle or head of the bar, traveling through the channel bed for some distance, and upwelling at the downstream end of the riffle or bar. Unlike the short distance shown in Figure 10, surface water may flow through the gravel over several hundred meters through riffles and entire gravel bars. Flow upwelling at the downstream end of gravel bars or in side channels is commonly a mixture of recently-downwelled water and older alluvial groundwater, yielding water with cooler temperatures in summer and warmer temperatures in winter relative to ambient stream water temperature. In higher latitudes, spawning salmon often seek out such upwelling zones because the bed (and their incubating embryos) does not freeze (e.g., Vining et al. 1985). Geist (2000) documented a strong preference among fall chinook salmon for hyporheic groundwater upwelling zones as spawning sites in the Hanford Reach of the Columbia River.

The physical and biological dynamics of hyporheic zones have rarely been monitored and are poorly understood on most rivers. Incision can be expected to influence the pattern of upwelling and downwelling along a channel. Where gravel deposits are thick, incision can lead to greater upwelling of cooler groundwater. Where the thickness of gravel over bedrock is limited, however, incision decreases (or in some case eliminates) the volume of gravel deposits over bedrock, reduces the volume of the hyporheic zone, and thereby reduces the available invertebrate habitat, and changes groundwater flow paths and the resulting nature of the groundwater-surface water exchanges of water, nutrients, organisms, and chemical constituents. These changes may have effects on the food web ecology of the river system.

Cumulative, Off-Site Impacts

The most severe effects of instream gravel mining may be considered as *cumulative* because they may become obvious only over time and extend beyond the limits of the mine site itself. Moreover, the effects of one mine may interact with those of other mines, yielding a net cumulative effect not apparent from a single mine.

The propagation of channel incision upstream and downstream from mines (often for distances of kilometers) on mainstem and tributaries, and through coalescing of incision effects (somewhat analogous to coalescing cones of depression from groundwater wells), individually subtle effects of gravel mines can become more visible and serious. Channel incision reduces the frequency of overbank flooding, and thereby reduces the opportunity for deposition of suspended sediment on the floodplain, and thus increases sediment delivery downstream. Dungeness Bay at the mouth of the Dungeness River has experienced rapid in-filling, evidently as a result of isolation of the channel from the floodplain by levees.

Effects of Small-Scale Extractions

Small extractions are often viewed as having only small, insignificant impacts. However, a small extraction on a small stream can take a large fraction of the annual load, and multiple small extractions on a larger stream can add up to be equivalent to a large proportion of total load. In some cases, small extractions may be practiced to avoid scrutiny entailed by fewer, larger extractions. A large timber company in northern California had 42 small extractions in one county in 1992, each declared at less than 764 m^3 (1000 yd^3) and thus exempt from most requirements of the state's surface mine reclamation act. Even when the extractions are all legitimately small, they can add up to have a significant cumulative effect on channel form, especially in small channels, where the sediment load would be naturally low.

Biological Consequences of Instream Gravel Mining

Biological consequences of instream gravel mining (as reported in various studies) can be summarized as follows. Direct, transient effects include increased fine sediment load to downstream reaches, commonly during low flow periods when flows would normally clear. The increased suspended fine sediment can directly affect respiration through gills, and impact invertebrate communities (e.g., Foshage and Carter 1973, Rivier and Seguier 1985). Because low flows are inadequate to disperse the sediment downstream, fine sediment from the mining tends to settle out and have more persistent effects, by infiltrating into spawning gravels (Carling and Reader 1982) and reducing incubation success, covering gravel riffles and eliminating invertebrate habitat, filling interstices of cobble beds and eliminating juvenile salmonid habitat, and filling pools, thereby eliminating important habitats for many organisms (Lisle and Hilton 1991).

Bar scalping reduces salmonid rearing habitat, side channel habitat preferred by salmonids, riparian canopy cover, benthic invertebrate habitat, and instream woody debris (Weigand 1991, Pauley et al. 1989). Removal of the riffle crest by bar scalping eliminates hydraulic control for the channel upstream leading to washout of upstream riffles and any salmon eggs present, and reach-scale channel steepening and bed incision. Chinook that would normally spawn at pool tailout riffles have been observed to relocate into the main channel after riffles were incised as a result of downstream bar scalping (Ken Bates, WDFW personal communication 2001). Channel-wide instream mining eliminates channel form and confinement, thereby eliminating channel complexity and resultant habitats. Removal of riparian vegetation from bars and banks leads to reduced shading (potentially increasing water temperatures on small rivers), reduced input of nutrients and insects from overhanging riparian vegetation (reducing productivity and food for salmonids), and reduced input of large woody debris (thereby reducing channel complexity and habitat). Channel incision caused by instream mining, especially by cumulative effects of mining at several sites over many years along the same reach, causes lowered alluvial groundwater tables, desiccation of riparian and floodplain vegetation, reduced channel-floodplain interactions, and elimination of processes of channel migration and the consequent habitat creation.

Any extraction of gravel from the channel bed interrupts sediment transport continuity and represents a loss term in the sediment transport budget, thereby inducing channel instability, and reducing the volume of downstream bars (Dunne et al. 1981). Associated channel incision changes the patterns and influences of alluvial groundwater-surface water exchanges along the river system. Depending on the geologic settings, this may decrease or increase base flows, with consequent impacts or benefits to habitat. Where the gravel thickness over bedrock is thin, incision can reduce or eliminate the hyporheic zone. Bed coarsening or fining can also result, and may further reduce the suitability of gravels for spawning by salmonids.

Effects of Floodplain and Terrace Pit Mining

Wet pit mining on floodplains (and terraces) involves conversion of land uses (typically riparian forest or agriculture) during and after the mining operation, channelization of the free-flowing river by levees and bank protection between pits and the river channel, and creation of warm-water lentic habitats that support non-indigenous fish species. So long as off-channel pits remain "isolated" from the free-flowing river, the principal effects on the channel are reduced channel migration and channel-floodplain interactions, physical habitat changes due to hydraulic effect of channelization, lack of natural channel banks and riparian vegetation and associated habitat along levees/bank protection works, trapping salmonids in pits and releasing non-indigenous fish (potential predators on salmonids) into the free-flowing river while the pit is hydraulically connected to the channel during floods, and changes in groundwater-surface water interactions potentially affecting temperature, water quality, and benthic invertebrate habitat and productivity. During excavation, if floodplain pits are kept dry by pumping, they lower local water tables, potentially dewatering nearby tributary channels and desiccating riparian vegetation and floodplain wetlands. When off-channel pits (inevitably) become captured by the channel, other impacts are introduced, including mixing non-indigenous predatory fish with salmonids, initiating bed erosion upstream by regressive knickpoint erosion and downstream by trapping bedload in the pit, and changing water temperature by mixing lotic with lentic waters.

Conversion of Existing Floodplain Habitat and other Land Uses

In Washington state, floodplain and terrace gravel pits typically each cover about 4 hectares (10 acres) of land, which in most cases supported riparian forest or agricultural land use prior to mine development. Displacement of these uses is a direct effect of floodplain pit excavation and mine site development. Where an aggregate pit lies entirely above the water table (a dry pit), it is possible to reclaim the pit to agriculture or housing, similar to other quarries or open-pit mines. However, floodplain pits typically intersect the water table for at least part of the year (wet pits), resulting in land-use conversion from farmland or riparian habitat to open-water pond. The scale of the landscape transformation effected by this pit mining is not widely appreciated, but becomes apparent by flying over river floodplains in light aircraft (Figure 31).

Collins (1995) documented a total of 152 floodplain pits along the Yakima River (counting those greater than 1.2 ha in size and deeper than the groundwater table). These pits, about 1 per kilometer of river, covered a total of about 580 ha (2,150 acres) of the Yakima River floodplain. Historical aerial photographs of the Yakima River show numerous meander scars and oxbow lakes indicating active channel migration over a wide floodplain area. Floodplain gravel pits, in addition to highway prisms and railroad grades and urbanization, reduce floodplain connectivity and restrict channel migration, which, along with reduced base flows from irrigation diversions, have substantially reduced habitat diversity (Eitemiller 1999). Stanford (1998) hypothesized that reduced connectivity between channel habitats and shallow back water habitats created by periodic flooding and upwelling groundwater is one of the key limiting factor for salmonid populations.

Figure 31. Oblique aerial view of the Ruddy reach of the Tuolumne River showing multiple floodplain gravel pits and the river channel, which itself flows through former in-channel pits (Photo by Kondolf 2000).

Channelization/Levee Effects

Floodplain pits are commonly excavated close to the currently active channel, where the best-sorted gravels are typically found. To maximize the floodplain area accessible for mining and to prevent the channel from eroding into the pits, the channel is commonly straightened and its banks stabilized with riprap. To prevent floodwaters from entering (and potentially destabilizing) the pits, levees are commonly constructed between the now-confined active channel and the pits. Thus, floodplain pits are typically accompanied by channelization.

Channelization has a host of negative impacts on river form and ecology (Brookes 1988). Those particularly relevant to salmonids include channel constriction, increased flow velocity and shear stresses and resulting reduced channel complexity, loss of high flow refuges, loss of riparian cover, and blow-out of channel gravels. Decreased surface area of pools and increased surface area of riffles have been documented as a consequence of channelization (Moyle 1976, Cederholm and Koski 1977). On the Tuolumne River, riffle slopes in channelized reaches between floodplain gravel pits are observed to be steeper than riffle slopes elsewhere, potentially driving riffles outside the range of acceptable depth and velocity conditions for salmonid spawning (Scott McBain, personal communication 2000).

Hyporheic Zone Groundwater Flux Changes and Water Quality Impacts

Even if the levees separating the pit from the channel remain intact, there is typically a strong hydrologic connection among the river, the pit, and the alluvial water table such that conditions in (or contamination of) the pit waters can affect water quality in the alluvial aquifer. Moreover, by exposing former intergravel water to the sun and air, the gravel pits may increase evaporative losses. How these losses would differ from transpirative losses from vegetation would depend on factors such as the type and density of vegetation, and the depth to water table. Effects of floodplain gravel pits on groundwater quality and hyporheic zone interactions along heavily-mined reaches of the Yakima River are now being studied by Professor Jack Stanford of the Flathead Lake Biological Research Station. Bank protection and levees to isolate pits from the active channel have reduced channel migration and channel-floodplain interactions, and altered hyporheic zone dynamics. Stanford's study seeks to characterize the degree of biophysical disconnection of the river from its floodplain as a basis for future efforts to restore channel-floodplain connections in key reaches. The effort has been initiated, in part, to test the hypothesis that improved survival of juvenile anadromous salmonids requires increased connectivity between channel and backwaters and fringing wetlands within the floodplain that are created by flooding and maintained by upwelling alluvial groundwater. On the Yakima River, irrigation returns flows have increased water temperatures in the free-flowing reaches, and habitats fed by cooler, upwelling groundwater from the hyporheic zone may provide temperature refugia for juvenile salmonids.

In July 1999, Central Pre-Mix Company, David Brown & Associates, Inc. and WDNR monitoring the effect of the Selah Lakes gravel pits on river temperature. Temperatures were recorded every 15 minutes at 45 locations in the Yakima River, groundwater wells, mine ponds, and various ditches and drainpipes, and two nearby weather stations. David Brown & Associates (2000a) analyzed the resulting data for 1999 and concluded that the Selah Lakes gravel pits were not contributing thermally to the river, but that the river was contributing thermally to the gravel pits. David Brown and Associates (2000b) measured water temperatures and modeled heat transfer via surface-groundwater exchange across the levee/berm between the Yakima River and two large gravel pits, the Newland and East Valley pits. Their study did not detect temperature effects of the pit on water in the river, and concluded that any river temperature effects of the pits would be small compared to a large weekly temperature cycling due to weekly variations in irrigation. David Brown & Associates (2000b: 100) implied that that the presence of 96 acres of ponds adjacent to the Yakima River could have a *cooling* effect on the Yakima River in this reach, "because it is thermodynamically easier for a moving river to exchange heat to a still pond, rather than the pond to exchange heat to the river." However, these studies have not been peer-reviewed to date and hyporheic zone impacts and temperature interactions remain poorly understood. Moreover, these studies did not address potential cumulative effects of multiple pits on river temperatures, nor potential pit effects on the full hydrological exchange. The modeling approach also assumed that there was a large exchange between hyporheic zone and the channel that overwhelmed any potential effect of the pits, but the actual magnitude of the exchange was not measured or verified in the field. The Yakima River has also warmed from other causes (principally irrigation diversions), so pit effects might be more difficult to detect than in a colder river in any case.

Creation of Lentic, Warm-Water Habitat

Gravel pits convert formerly lotic (flowing) habitats into lentic (stillwater) habitats. In many climates, off-channel pits heat up in the summer and provide habitat for warm water fish that prey on juvenile salmonids. Along tributaries to the San Joaquin River in California, abandoned gravel pits host large populations of largemouth and smallmouth bass (*Micropterus salmoides* and *M. dolomieui*). While these pits are temporarily connected to the channel during floods, they serve as a source of warm-water fish to the main channel, and juvenile salmon can become stranded in the pits. Although interactions between fish populations in gravel pits and the adjacent free-flowing river have not been extensively studied in Washington state, if at all, predation of juvenile salmonids by warmwater introduced fishes has been studied. McMichael et al. (1999) showed, for example, that predation on juvenile salmonids by predaceous warm-water fishes in the Lower Yakima River is substantial. Smallmouth bass were estimated to consume about 0.5 million salmon smolts per year, resulting in an annual loss of about 1,350 adult salmon. McMichael et al. (1999) recommended reducing the temperature of the Lower Yakima River by 2^{o} C (3.6^{o} F) to reduce the density of predatory warm-water fishes. Channel-floodplain disconnection and the cumulative effect of numerous floodplain gravel pits on the Yakima has probably resulted in a reduced hyporheic zone volume, and reduced the temperature-moderating effect of natural hyporheic zone interactions. Off channel pits pose the greatest problems when they are "captured" by the channel (as discussed below), giving the populations of warm-water exotic fish excellent access to their prey, out-migrating salmon smolts.

Floodplain Pit Capture

Another potential effect of floodplain pits arises if the active river channel begins to flow through the old gravel pit, effectively transforming the floodplain pits into instream pits. This so-called *pit capture* occurs when the levee or strip of land separating the pit from the channel is breached by lateral channel erosion or by overflowing floodwaters. Pit capture is a common phenomenon, documented at 12 of 25 recently abandoned floodplain mining sites studied in northern Alaska (Woodward-Clyde Consultants 1980). In general, pit capture is inevitable for floodplain pits (though not necessarily for terrace pits, which are usually higher in elevation and farther from the channel) as channel migration progresses over the long term, and is most likely or rapid when the pit lies in a shortcut for the flooding river, such as the inside of a meander bend, and when the pit is large relative to the hydraulic gradient of the river, such that the upstream end of the pit is much lower than the adjacent channel.

When pit capture occurs, the formerly off-channel pit is converted into an in-channel pit. Aquatic habitat in the abandoned, now dewatered channel is lost and the indirect effects of instream mining can be expected, notably propagation of incision upstream and downstream of the pit (Galay 1983). Captured pits become lakes within the river, transforming lotic environments into lentic environments, thereby inducing changes in the ecology of the reach. Captured gravel pits in the Naugatuck River, Connecticut, are now virtual lakes with seasonally stagnant water and depressed dissolved oxygen levels; based on estimated bedload transport rates, the pits are expected to persist for hundreds of years (MacDonald 1988).

The effect of pit capture on predator-prey dynamics has been studied in California Rivers. The Merced River, draining the western slope of the Sierra Nevada in Central California, flows through at least fifteen gravel pits, of which seven were originally excavated in the active channel, and eight were excavated on the floodplain and subsequently captured the channel (Vick 1995). Juvenile salmon migrating ocean-wards become disoriented in the quiet water of these pits and suffer high losses to predation by exotic species. On the nearby Tuolumne River, which flows through a similar number of pits, a 1987 study by the California Department of Fish and Game estimated that juvenile chinook salmon migrating oceanward suffered 70 percent losses to predation (mostly in 15 captured gravel pits) in the three days required to traverse an 80 km (50 mi) reach from LaGrange Dam to the San Joaquin River (EA 1992).

Documented Pit Captures in Washington

Pit captures have occurred on many rivers in Washington in recent decades, and an example of the 1971 pit capture on the Yakima River featured in the textbook *Water in Environmental Planning* (Dunne and Leopold 1978) has become perhaps the best known pit capture in the literature.

Norman et al. (1998) documented pit captures occurring in 1995 and 1996 at five sites on the Yakima River, two sites on the East Fork Lewis River, two sites on the Cowlitz River, the Wynoochee River, and Salmon Creek (Table 8) (Norman et al. 1998). Following capture of the gravel pit on Salmon Creek (just upstream of I-5, north of Vancouver) in 1996 (Figure 32), the upstream channel incised and incision progressed 400 m (1300 ft) upstream to a concrete sill under a county road bridge, creating a 2-m-high (6.5 ft) barrier to fish migration (Figure 33). Channel incision mobilized gravel from the bed, which was subsequently deposited in the upstream end of the captured pit.

Table 8. Pit captures in Washington State (Norman et al. 1998)

Location or operation	River	Year	Location	Date mined	Acres
Upstream Ridgefield pits	East Fork Lewis	1995	sec. 19, T4N, R2E	1960s	6
Ridgefield pits	East Fork Lewis	1996	secs. 13, 24, T4N, R2E	1980s-90	70
Salmon Creek Park ponds	Salmon Creek	1996	sec. 35, T3N, R1E	early 1970s	5
Pits upstream of Toledo	Cowlitz	1995,1996	sec. 10, T11N, R1W	ongoing	20
Gravel pits at Toledo	Cowlitz	1995,1996	secs. 8, 17, T11N, R1W.	ongoing	108
Mouth of Wynoochee River	Wynoochee	1984	sec. 18, T17N, R7W	1960s	20
Walker pit	Yakima	1996	sec. 36, T11N, R20E	ongoing	12
Parker pit	Yakima	1996	sec. 20, T12N, R19E	1980s	35
Selah Gap pits	Yakima	1996	sec. 31, T14N, R19E	ongoing	250
Gladmar Park	Yakima	1996	sec. 13, T18N, R17E	1960s	30
I-90 pits	Yakima	1996	sec. 29, T18N, R18E	1960s	20

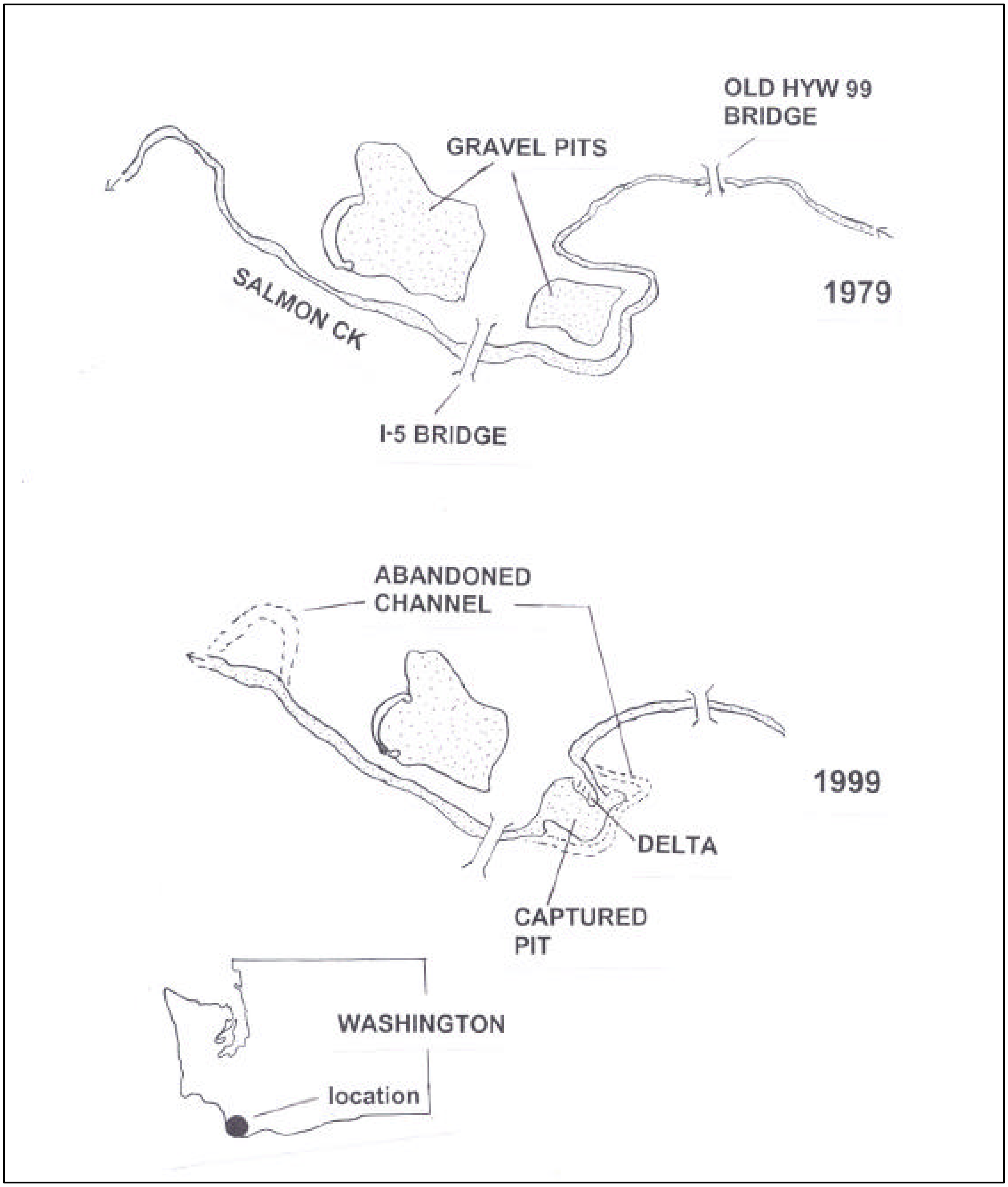

Figure 32. Map showing capture of gravel pit by Salmon Creek and location of subsequent regressive erosion upstream to a county bridge, creating a 2-m-high barrier to fish migration.

(a) 1979: mining completed. (b) 1999: three years after pit capture by Salmon Creek, a delta has formed where Salmon Creek enters the pit. Headcut moved about 400 m upstream to a county road bridge. Approximate scale for 1979 map: one cm = 80 m (one inch = 660 ft). For 1999, map: one cm = 96 m (one inch = 800 ft).

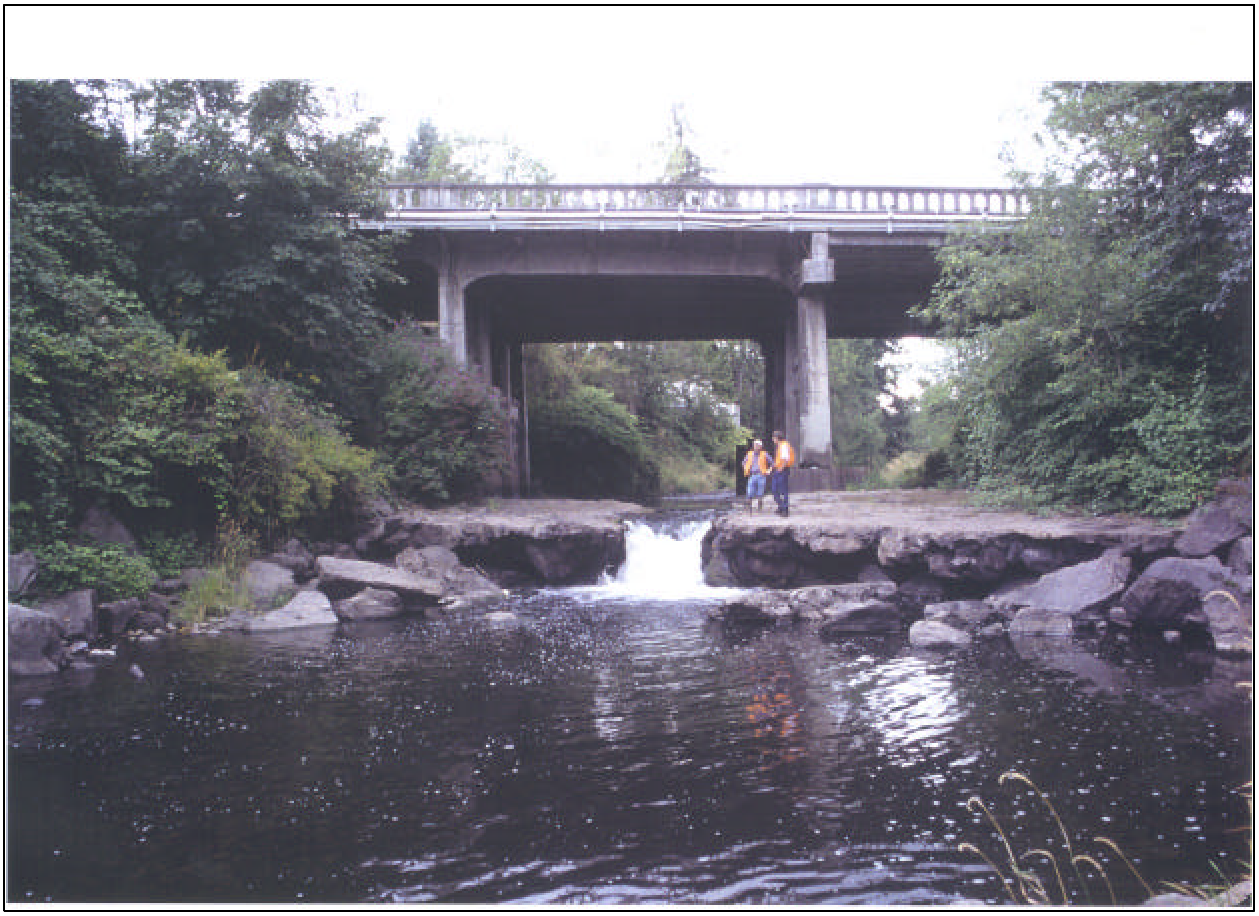

Figure 33. Headcut caused by regressive erosion upstream from captured gravel pit on Salmon Creek, near Vancouver, Washington (Photograph by Kondolf 2001).

The Cowlitz River had a complex, multi-thread channel near Toledo in the first half of the 20th Century, prior to extensive gravel mining. However, the river is presently confined between dikes separating the channel from the gravel pits. Levee breaching and pit captures by the Cowlitz River in 1995 and 1996 caused the channel to avulse into its former (1854) channel and left a number of homes isolated in 1996 (Figure 34).

The Yakima River captured five large gravel pits and numerous smaller pits during the 1996 flood, including the Walker, Parker, Selah Gap, Gladmar Park, and I-90 pits (Norman et al. 1998). The bottom elevation of the 3-m-deep (10 ft) Parker ponds was only slightly lower than the adjacent channel elevation, so little upstream incision resulted from pit capture. The Yakima currently has a sinuous, multichanneled course through the Parker ponds. Similarly, the bottom elevation of the Gladmar pits was only slightly lower than the adjacent channel, and little upstream incision resulted. In Yakima, the 20 ha (50 ac) Beech St. pit along the right bank is over 30 m (100 ft) deep, leading to concern about potential channel impacts if it was captured by the river. During the 1996 flood, emergency riprap was placed on the levee to prevent its breaching.

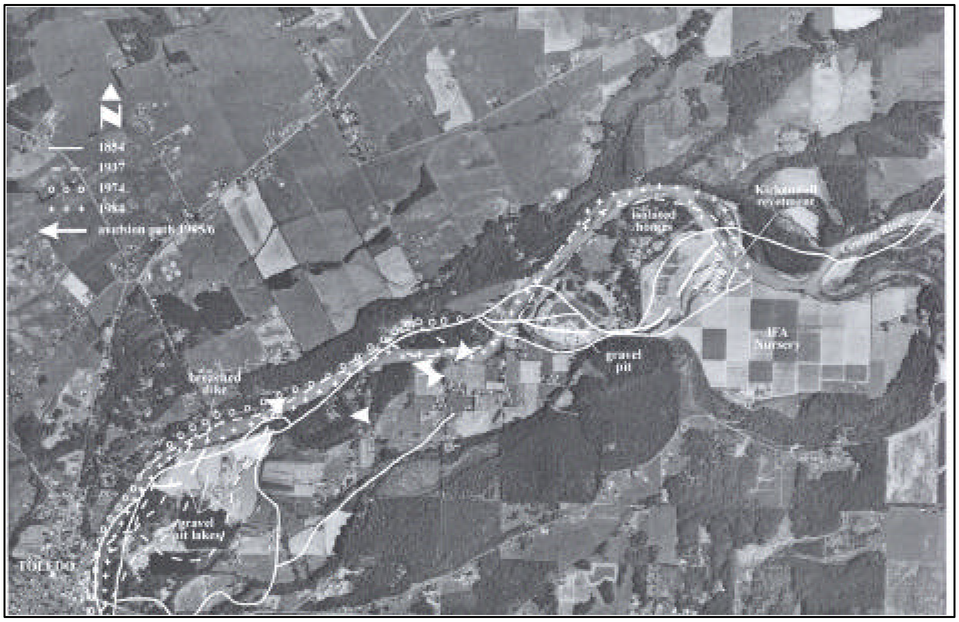

Figure 34. Vertical aerial photograph (July 1996) of the Cowlitz River from Toledo, Washington, upstream, annotated to show flow paths of the 1995 and 1996 floods (Reproduced from Norman et al. 1998, used by permission).

The channel broke through the Kirkendoll revetment into its former channel (ca. 1854), and captured gravel pits.

Gravel has been mined on the left bank floodplain of the Yakima River above Selah Gap since 1971, with pits now occupying about 100 ha (250 ac), with maximum extraction depths of 7.6 m (25 ft) (Norman et al. 1998). The armored levee separating the pits from the channel breached during the February 1996 flood, and the Yakima River captured the pits (Figure 35). Incision rapidly propagated upstream, with about 2 m (6.5 ft) of incision evident upstream, releasing an estimated 262,400 m^3 (400,000 yd^3) of gravel eroded from the channel bed upstream, of which about ¾ was deposited in the pits (as a layer1.8 m (6 ft) thick over an area of (33 ac)) and about ¼ deposited in gravel bars and private lands upstream of the pits (Norman et al. 1998).

The East Fork Lewis River captured a left bank floodplain pit on the inside of a meander bend in 1995, abandoning a right meander bend (Figure 36) then in late 1996 avulsed through a complex of multiple pits on the left bank floodplain (Figure 37). As a result of these avulsions, about 1,500 m (4,900 ft) of channel (formerly used by steelhead and salmon) was abandoned, and the river now flows sluggishly through a series of deep pits (Norman et al. 1998). Also resulting from these avulsions was channel incision, as visible at the downstream end of the channel abandoned by avulsion in 1995 (Figure 38).

Pit capture along this reach can be viewed as inevitable, given the record of historical channel migrations since 1954 (Figure 39). Moreover, the steepness of the bluffs bordering the floodplains implies that the channel has migrated entirely across its floodplain frequently enough in recent centuries to undercut the bluffs and maintain the freshness of the land form.

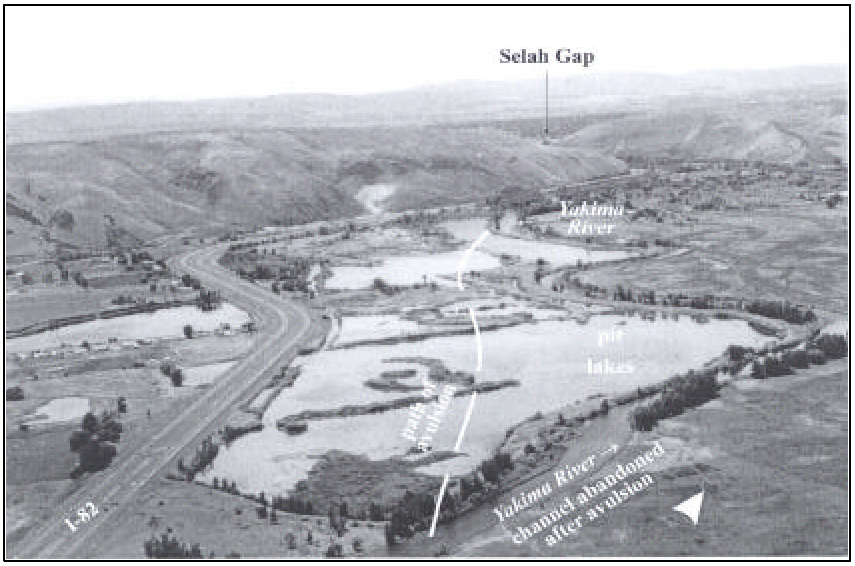

Figure 35. Oblique aerial photograph looking downstream along the Yakima River and gravel pits near Selah Gap in 1994 (Reproduced from Norman et al. 1998, used by permission).

The path of the river avulsion and pit capture in February 1996 is superimposed.

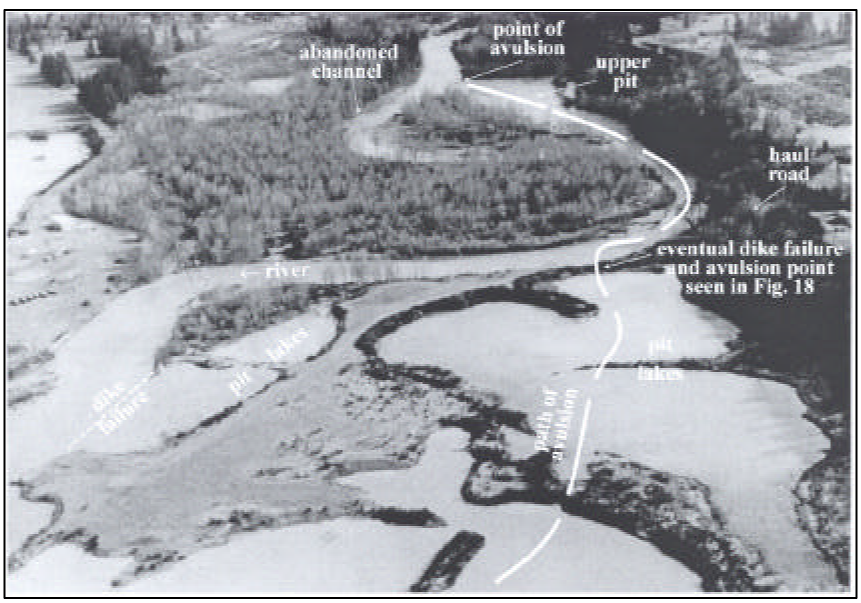

Figure 36. Oblique aerial view upstream along the East Fork Lewis River during the February 1996 flood (Photograph by Dan Miller, reproduced with annotations from Norman et al. 1998).

Noted is the abandoned meander bend (cut off in 1995) and the path of the subsequent avulsion.

Figure 37. Vertical aerial photo of the East Fork Lewis River in November 1997, showing the path of the 1996 avulsion (Reproduced from Norman et al. 1998, used by permission).

The right bank across from "B" is the location of Figure 38, a 2001 photo of the lower end of the abandoned meander bend. "C" is the point at which the left bank levee breached.

Figure 38. View downstream along right bank of the East Fork Lewis River, at the downstream end of the former main channel, which cut off in 1996 when the river captured the gravel pits on the left bank (Photograph by Kondolf 2001).

The man on the right stands on the former channel bed, the man on the left stands on the edge of the current channel. The current channel has incised about 1.5 m from its pre -cutoff elevation.

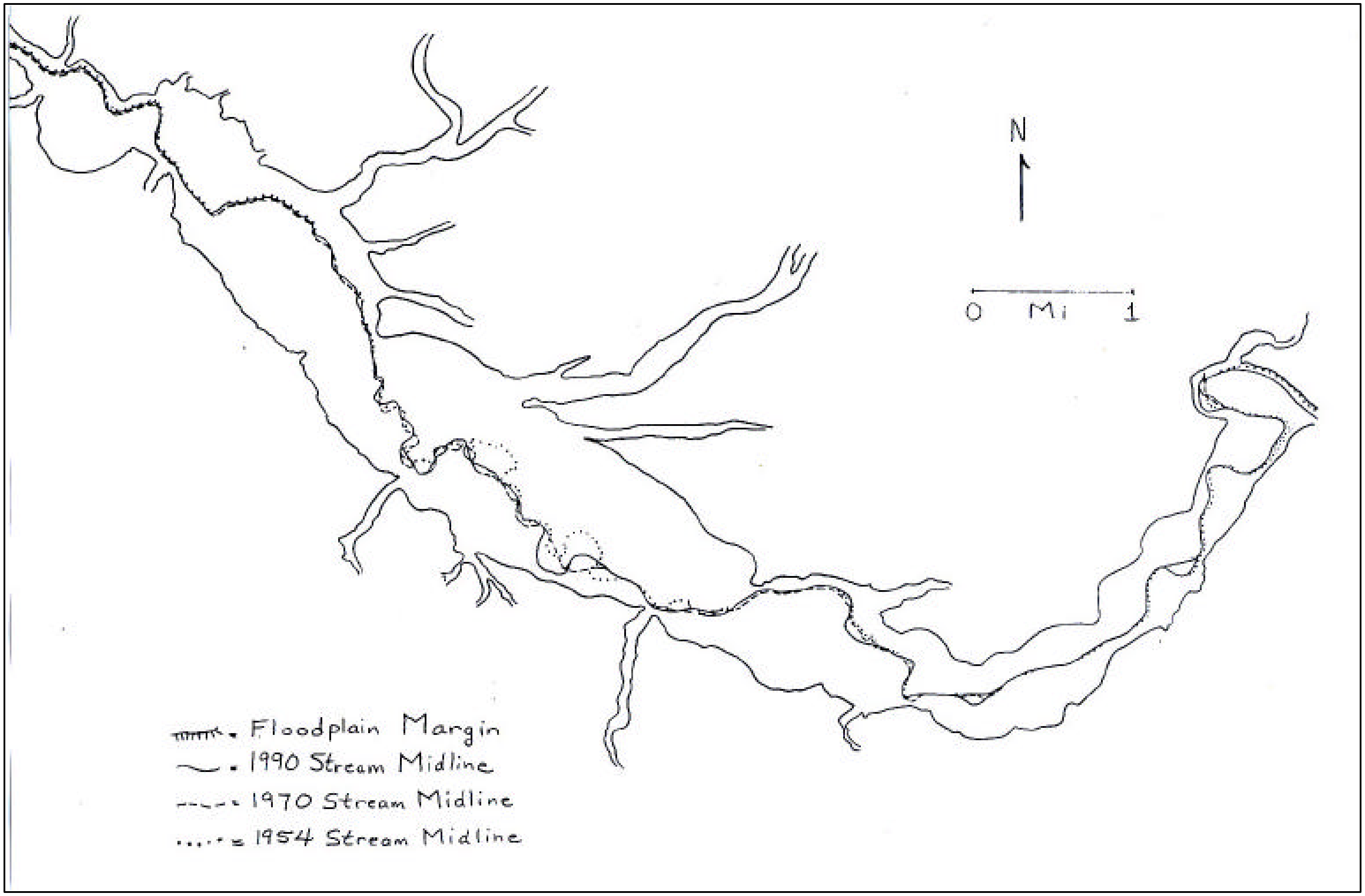

Figure 39. Map showing channel centerlines of the East Fork Lewis River in 1954, 1970, and 1990, and bluffs bounding the floodplain, as mapped from US Geological Survey 1:24,000-scale topographic maps by Kondolf and Kelso (1996).

The Clackamas River in Oregon also captured an off-channel pit in 1996, and 2 m (6.5 ft) of incision was documented about 1.5 km (1 mi) upstream (Figure 40), undermining a building at the gravel mine site (Figure 41).

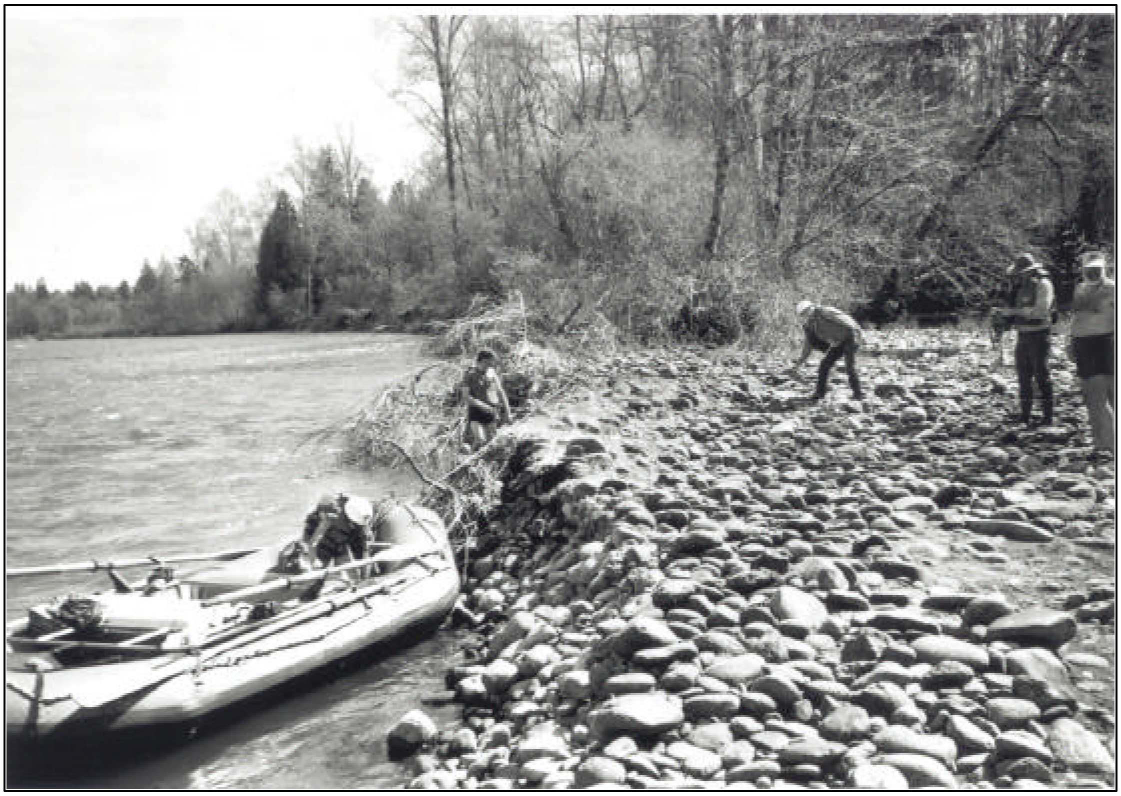

Figure 40. Incision of Clackamas River approximately 1.5 km (one mile) upstream of a captured gravel pit near Barton, Oregon (Photograph by Kondolf, April 1996).

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 knickpoint from the gravel pit. View upstream.

Specific Considerations for Alluvial Fans

Alluvial fans occur where a reduction in channel slope or confinement reduces transport competence and results in deposition. They are called “fans” because of their plan form, which resembles a fan radiating outward from the point at which the channel gradient and/or confinement reduces. Alluvial fans are the subaerial (i.e., surface) equivalents of deltas (which are deposited under water, with different characteristic forms and depositional patterns). The fan form is created as the currently active channel deposits sediment and aggrades until it is higher than the surrounding fan surface. At some point, this channel becomes unstable, and the main flow shifts from this channel to another course, until that one also becomes unstable from aggradation, and the main locus of deposition shifts again, thereby incrementally building the fan form in plan view, and sloping surface in profile. Thus alluvial fans are the result of many coalescing channel deposits radiating in virtually every direction from the point source (generally the transition from confined mountain channel to unconfined valley). Characteristically, the upper (proximal) part of the fan consists of the coarsest sediment, with the lower (distal) part of the fan having progressively finer and finer sediment. The process of deposition and abandonment that builds up alluvial fans is inherently unstable, a fact that has led to channel changes on alluvial fans that, while perfectly natural from the physical process point of view, may be catastrophic in human terms. Recent examples include the Aràs Torrent fan in the Pyrenees, in which a channel avulsion in 1996 killed 86 in a campground (Batalla and Sala 1997, Batalla et al. 1999).

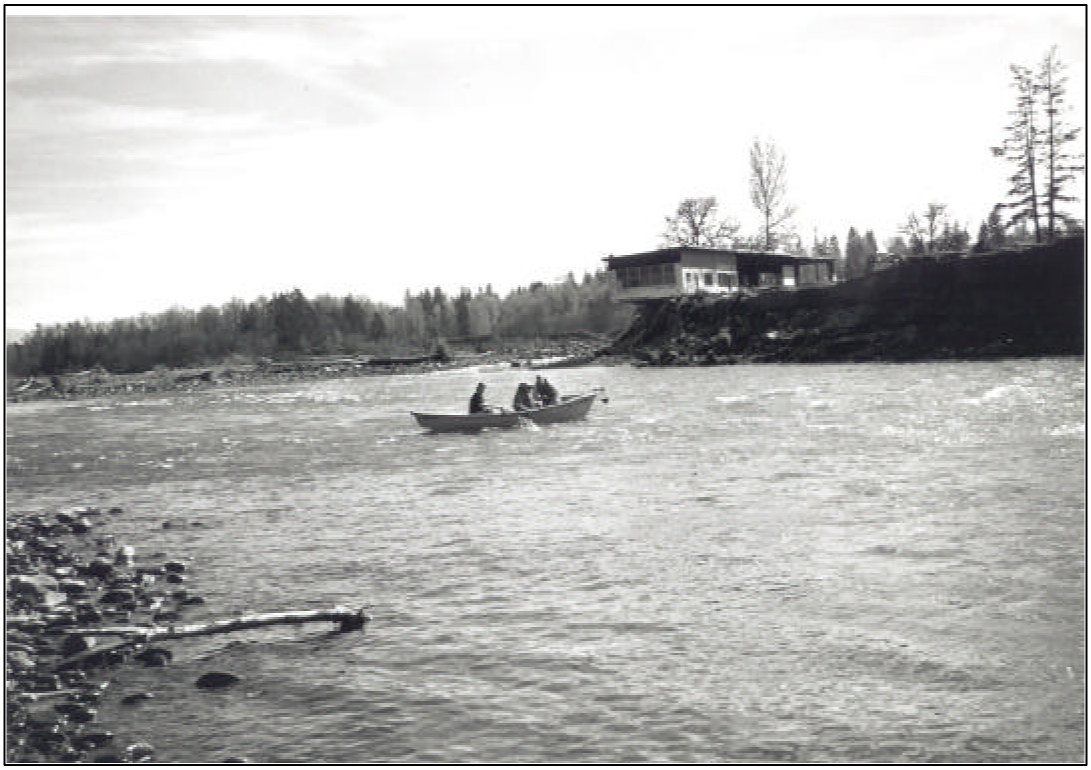

Figure 41. Building undercut by bank erosion as the Clackamas River flows through a captured gravel pit near Barton, Oregon (Photograph by Kondolf, April 1996).

Alluvial fans are common features at the edge of large river floodplains in the post-glacial landscape of Washington, were steep streams arriving from bedrock hills encounter a sharp gradient decrease and deposit most of their coarse (bed) load, with most of the fine-grained load continuing downstream in suspension. As natural sites for gravel accumulation, they have been favored spots for extraction, including the small fans of steep streams tributary to large floodplain rivers. Since they are loci of aggradation, they are probably better sites than most for gravel extraction, but the high potential for instability is a concern.

If gravel is extracted from former channels of an alluvial fan, there is an increased risk of channel avulsion and propagation of incision and instability. On the Tujunga Wash near Los Angeles in 1969, flood flows diverted into an urbanized distributary channel of the wash, entered a large gravel pit situated near the distributary channel and caused knickpoint erosion upstream from the pit and rapid lateral channel migration. Bed degradation by knickpoint erosion extended from the gravel pit to about 915m (3,000 ft) upstream and caused failure of three highway bridges (Figure 42). Seven homes and a residential street were destroyed by the associated lateral migration (Scott 1973). If extraction occurs in the currently active channel, instability may propagate upstream and downstream from the pit, though the risk of avulsion may be reduced by virtue of limiting aggradation in the current channel. Downstream, the channel may be starved of coarse sediment and may respond through incision, etc.

Figure 42. Collapse of Foothill Ave Blvd during the flood of 1969 in Tujunga Wash, Los Angeles (Source: Scott 1973).

Specific Considerations for Braided Rivers

Braided channels are unstable, unvegetated channels in which multiple threads (subchannels) of water, termed anabranches, are separated by unvegetated bars that are inundated at relatively frequent flows, generally less than Q_2 or even Q_1. Anabranches join and split apart repeatedly (and randomly) in a downstream direction, migrating across the valley floor by bank erosion and avulsion of anabranches. Braided channels reflect a high supply of sand and gravel, erodible banks, high energy, and, frequently, high variability in discharge (Leopold and Wolman 1957, Thorne 1997). Anastomosing rivers are multi-channeled, but with anabranches separated by stable, vegetated islands. Anastomosing channels can be quite stable, and are often found in low-energy systems.

The nature of braided channels and the implications of their dynamic behavior for stability of floodplain gravel pits were cogently summarized by Dunne and Leopold (1978), whose description of channel migration, avulsion, and potential for pit capture on the Yakima River reads like a prediction of the events that followed two decades later.

Among non-geomorphologists, there is a widespread perception that braiding implies aggradation. While aggrading channels are often braided, braided channels need not be aggrading, only unstable and dynamic. In some cases, braiding can result from reduction in bank stability, as for example removing or desiccating bank vegetation (Kondolf and Currey 1986). Extraction of gravel or attempts to confine these channels with rock dikes commonly produces instabilities upstream, downstream, or on the opposite bank (Galay 1998). Given the high energy of braided channels, incision effects tend to propagate upstream rapidly during floods. As with alluvial fans, the potential for capture of off-channel pits may be high.

Cumulative, Off-Site Impacts

As in-channel mining is increasingly discouraged or prohibited, mining of floodplain pits is encouraged as a less damaging alternative. While most would agree that floodplain pits, so long as they remain isolated from the channel, do not have the same impacts as instream extraction, the cumulative effects of pits are not fully understood. Similar to the cumulative effects of channel incision caused by numerous instream channel mines in one river reach or drainage network, the most severe effects of floodplain and terrace pit gravel mining may extend beyond the limits of the mine area and period of active mining.

The view of floodplain pits as mostly impact-free is largely a question of scale, both in time and magnitude. Gravel pits are typically proposed and permitted one at a time, on a site-specific basis, without projecting 50 or 100 years into the future to imagine what the floodplain will be like if current trends continue. Off-channel pit extractions are commonly enormous, frequently reaching depths of over 18 m (60 ft) (and over 30.5 m (100 ft) in some cases, such as the Beech St pit in Yakima). Thus, if the pit is captured, the potential consequences on the channel may be considerable, producing a long-term depletion of sediment supply to downstream reaches. Given that the volume of a single pit on the Yakima River is roughly equivalent to about 100 years of sediment load, a captured pit could be capable of capturing all bedload for some time (Ken Bates, WDFW personal communication 2001). Moreover, channel incision and instability induced upstream of captured gravel pits could trigger other pit captures, resulting in widespread and long-term cumulative effects.

Even if pit capture does not occur, the cumulative conversion of floodplain to open water pit can be considerable. Collins (1995) mapped numerous floodplain gravel pits visible in aerial photographs of the Yakima River. In a 20 km (12 mi) reach (km 238-258) near Ellensburg, for example, he counted 44 pits covering a total of 168 ha (415 acres), an average of 2.2 pits per km and 84 ha pit per km. While individually many of these pits would be considered relatively insignificant, the net effect of multiple pits in one reach results in cumulative, off-site impacts. Bank protection constructed to protect these pits has reduced the potential channel migration zone, resulting in reduced riparian habitat values on a large percentage of the Yakima's active floodplain. Numerous pits also change hyporheic zone dynamics and groundwater flow patterns, effects that remain largely undocumented.

From the point of view of salmon viability, the real threat is pit capture, whose likelihood must in a general way increase with increasing extent of floodplain gravel pits. If viewed over a sufficient time period of a century or two or three, it is probably not a question of *if* pits are captured by the channel but *when*. As the number of captured pits increases, more habitat for potential predators on salmonids is created at more locations along the river system. Predators may thereby inhabit a larger and larger percentage of the free-flowing river and backwater areas over time.

Biological Effects of Floodplain and Terrace Pit Mining

So long as off-channel pits remain "isolated" from the free-flowing river, the principal biological effects of floodplain and terrace pit mining are the conversion riparian forest to open pond habitat, reduced habitat complexity in the channel and loss of dynamic channel migration processes by levees and bank protection, lack of natural channel banks and riparian vegetation along hardened banks, changes in the hyporheic zone dynamics potentially affecting stream water temperature and water quality, increased potential for contamination of the alluvial aquifer due to the operation of equipment, spills, and the direct route to groundwater through the pit, trapping salmonids during floods, increasing habitat for warmwater predatory fish that escape into the river during floods, and loss of floodplain wetlands and dewatering of tributaries due to lowered water tables.

There are other biological consequences when off-channel pits eventually become incorporated into the channel by being "captured" by the channel, including exposing juvenile salmonids to heavy predation by exotic warm-water fish, initiating bed erosion upstream by regressive knickpoint erosion and downstream by trapping bedload in the pit, and changing river water temperature by mixing lotic with lentic waters. As the river abandons its natural channel, the aquatic habitats there are lost, as the river instead begins to flow sluggishly through the captured pits. The natural channel habitats lost can include important spawning and rearing habitats, as noted by Norman et al. (1998). Channel incision initiated by pit capture (and cumulative effects of numerous pit captures over time) reduces channel-floodplain connectivity and habitat-creating channel migration, reduces area of spawning habitat, reduces volume of downstream gravel bars, reduces the volume of the hyporheic zone, and affects hyporheic zone dynamics important for benthic invertebrate production and temperature and water quality mediation in river systems.

Freshwater Navigational Dredging

Purpose and Extent

Dredging to maintain navigational channels in Washington occurs mainly in salt and brackish waters and is thus covered primarily by the Marine Dredging Issues White Paper. Freshwater navigational dredging occurs in the Cowlitz and Columbia Rivers (Norman et al. 1998), and in the Snake River upstream to the international ports of Lewiston and Clarkston (USACE 2000).

Navigational Dredging along the Snake River

From 1961 to 1999 about 7 million m^3 (9.2 million yd^3) of sediment was dredged from the Snake River and McNary Reservoirs, mostly for navigational channels, harbors, and marinas (USACE 2000). Disposal sites for the approximately 3.6 million m^3 (4.7 million yd^3) dredged from about 1961 to 1982 was not reported, but of the material dredged since about 1982, 1.4 million m^3 (1.9 million yd^3) was disposed in upland sites and 2.0 million m^3 (2.6 million yd^3) was disposed in the riverine reservoirs outside the navigational channels (USACE 2000). The USACE (2000) proposed to dredge another 185 thousand m^3 (244 thousand yd^3) in 2000-2001, and to dispose of the spoils in the reservoirs. The Environmental Assessment (USACE 2000) emphasized expected habitat benefits from disposing of sand to cobble-sized sediment in shallower parts of the reservoirs, but did not address issues such as predation of juvenile salmon by warm water fish, nor potential downstream effects of sediment starvation.

Navigational Dredging along the Columbia River

The USACE has dredged sediment from the lower Columbia River for navigation at least since 1904. Through 1955, most of the dredge material was disposed on land, but since 1956 most disposal has been to deepwater sites offshore. Since 1939, an average of 2.5 million m^3/y (3.3 million yd^3) of sediment was removed by dredging (George Kaminsky, Washington Dept. of Ecology, Olympia, unpublished data, 2001).

The likely cumulative effects of this dredging on the sediment budget of the lower Columbia River are appreciated only when viewed in light of the combined effects of upstream dams on the river's sediment budget. The pre-dam (pre-1934) sand supply to the lower river was about 4.3 million m^3 (5.7 million yd^3) per year, but sediment trapping in dams has reduced the sediment supply by 66% to only 1.4 million m^3 (1.8 million yd^3) per year. Thus, the post-dam dredging rate of 2.5 million m^3 (3.3 million yd^3) has exceeded the post-dam sand supply by 80% (Kaminsky, unpublished data).

The USACE has now proposed to deepen the navigational channel from 12 m (40ft) to 13 m (43ft) along the lower 18.5 km (11.6 mi) of the Willamette and lower 166 km (103.5 mi) of the Columbia River below Vancouver, Washington (http://www.sei.org/columbia/background.html).

This net increase in depth will require a significant increase in dredging, removing from storage in the river channel of 47.4 million m^3 (63 million yd^3) of sand over a 20-year period, for an average removal rate of 2.3 million m^3/yr for 20 years. An additional 12.2 million m^3 (16 million yd^3) of sand is to be dredged from the estuary (0.6 mill ion m^3/y for 20y), and 30.6 to 53.5 million m^3 (40-70 million yd^3) from the river mouth. Total annual dredging from the river channel, estuary, and mouth is proposed to be 5.1 million m^3/yr, about 3.5 times the post-dam sand supply (Kaminsky, unpublished data).

The Columbia River is the source of sand for a littoral cell extending 160 km (100 mi) along the Pacific coast, from Point Grenville, Washington, to Tillamook Head, Oregon. The coast along this cell has experienced accelerated erosion, with recent coastal erosion in the Westport area alone costing $30 million in repairs. The Southwest Washington Coastal Erosion Program is currently compiling data on coastal erosion rates.
(http://www.ecy.wa.gov/programs/sea/swce/intro.html).

A scientific review panel is now reviewing potential environmental effects of the USACE's proposed Columbia River dredging project (http://www.sei.org/columbia/scipanel.html).

Agricultural Drainage Dredging and Channelization

Purpose and Extent

Natural and human-made drainages on agricultural land are typically channelized and often dredged periodically to accommodate efficient crop and irrigation system layout, lower water tables, and reduce the frequency of overbank flooding. Drainages on floodplain agricultural lands are often developed in remnants of riverine side channels. We found no information on the extent of agricultural channelization and dredging in Washington, and little information on its effects. However, the practice (and its effects) are probably widespread throughout the state.

Effects

Channelization effects at various scales were comprehensively reviewed by Brookes (1988), who documented channel incision and consequent bank undercutting, channel simplification, increased flow velocities, and reduced aquatic habitat area, among other impacts in the Puget Sound region of western Washington. Chapman and Knudsen (1980) examined salmonid habitat and biomasses in altered and control sections of small channelized streams, including agricultural drainages. Channelization significantly reduced riparian canopy cover, channel sinuosity, wetted area, and woody bank cover.

Biological Consequences

For the Puget Sound streams studied by Chapman and Knudsen (1980), total habitat area for salmonids declined in channelized reaches compared to control reaches. Channelization reduced winter habitat for salmonids. Biomass of coho salmon (*Oncorhynchus kisutch*) declined in severely damaged reaches. Reduction of riparian canopy cover led to increased standing crop of salmonids in some cases, suggesting that salmonid production may be light-limited in many western Washington streams.

Because agricultural drainage channels (and the attendant channelizing of natural channels) are ubiquitous in agricultural regions of Washington, these effects are probably among the most widespread in the state. Perhaps because of their ubiquity and the small size of most of the channels affected, they have largely escaped scientific study, an unfortunate oversight when so many native fish populations are threatened with extinction.

Management of Instream Gravel Mining

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 (Galay 1983). 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. However, in cases where extraction rates are not so much greater than other components of the sediment budget, gravel mining effects may be more subject to different interpretation.

On Stony Creek, California, 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 pre-dam sediment supply by 200-600 percent, and exceeding the post-dam sediment supply by 1000-3000 percent) produced incision of up to 7 m (23 ft) centered in the mining reach near the Highway 32 bridge, after intensification of gravel mining in the 1970s (Kondolf and Swanson 1993).

Lag in Channel Response to Gravel Mining

Bedload sediment transport occurs as a power function of discharge, so variations in discharge produce even greater variations in sediment transport. In most rivers, the majority of sediment transport occurs during a small percentage of the time, and this “episodic” nature of sediment transport is greater the more variable is the flow regime.

The effects of instream gravel mining may not be obvious immediately because active sediment transport is required for the effects (e.g., incision, instability) to propagate upstream and downstream. Given that geomorphically-effective sediment transporting events are infrequent on many rivers, there may be a lag of several or many years before the effects of instream mining are evident and propagate along the channel. Moreover, the initial incision tends to oversteepen and erode banks, and to induce regressive erosion up tributaries, thereby bringing sediment into the channel, and temporarily buffering the effects of sediment removal. Thus, gravel mines may operate for years without apparent effects upstream or downstream, only to have the geomorphic effects manifest years later during high flows. Similarly, rivers are often said to have "long memories", meaning that the channel adjustments to instream extraction or comparable perturbations may persist long after the activity itself has ceased.

Strategies to Regulate Instream Gravel Mining

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 past permits, 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.

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 might be desirable, the inherent complexity of sediment transport and channel change and the lack of adequate data on channel form, sediment transport, and gravel extraction overtime, make 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 careful regulation of gravel mining in rivers by states.

The “Replenishment Rate” Concept

Another approach to managing gravel mining 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 popular 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.

Dunne et al. (1981) stressed because actual bedload transport is variable from year to year, estimated average annual bedload inflow rates may not be applicable in most years. Replenishment can be estimated year-to-year, either riverwide (based on sediment rating curves), or based on site-specific deposition. The latter approach is used on the Mad River in California, where a committee of scientists visits extraction sites annually, reviews semi-annual cross section survey data, estimates the amount of deposition over the flow season, and recommends an extraction amount, location, and method (Klein et al. 1999).

In estimating annual (or annual average) replenishment rates, it is important to recognize that using sediment transport equations yields an estimate of theoretical bedload sediment transport *capacity*, which is commonly less than actual load, as the latter is limited by actual sediment supply from the basin.

Instream Mining as a Flood Control and/or Channel Stabilization Tool

Gravel extraction is widely perceived to yield flood control benefits, but there is little hard evidence that the perceived benefits are real or more than ephemeral. The change in sediment mass balance effected by instream gravel mining can be utilized as a tool for river control on reaches with high rates of aggradation, such as the Waimakariri River near Christchurch, New Zealand, which drains the rapidly eroding Southern Alps, with denudation rates of 20 mm/yr (0.8 in/yr). From 1929 to 1973, the Lower Waimakariri River aggraded an average of 2.9 m (9.5 ft), while aggregate extraction averaged 5.9 m (19 ft) and prevented greater aggradation and possible avulsion through the city (Griffiths 1979). However, most rivers do not have such high rates of bedload sediment supply, and the New Zealand literature also reports that mining-induced incision has undermined infrastructure, such as flood control embankments (e.g., Soil & Water 1985). Presumably, lower rates of gravel extraction could be used to control lower rates of aggradation, although no such successful approach has been documented.

When human settlement occurs on former active channel surfaces at virtually the same elevation as the current active channel, the potential for flooding and erosion damage to property is high (Figure 43). This situation often leads to calls for in-channel gravel extraction, levee construction, and channel straightening, with probable negative consequences for aquatic habitat.

Flood control benefits have commonly been cited as justification for instream mining projects (e.g., Bissell and Karn 1992). The fact that WDNR charges a royalty on gravel removed from rivers except when the removal is for purposes of flood control (WDNR 1989) may encourage articulation of perceived flood control benefits from instream mining, but the idea that removing gravel from the channel increases flood capacity appears to be a widely held view among members of the public.

In evaluating the potential flood control function of instream mining, it is important to place the reach in a larger basin context. Referring to Schumm's (1977) idealized zonation of rivers (Figure 2), it stands to reason that mining-induced channel incision (and widening) in the transport zone would increase channel dimensions and therefore channel flood capacity (although a number of factors can render this effect insignificant as discussed below). However, reaches in the zone of deposition, including local depositional reaches within the transport zone, such as expansions, points of geologically controlled reductions in gradient, are likely to "re-fill" quickly with gravel, potentially during a single flood. In fact, it is such zones of abruptly reduced shear stress that Dunne et al. (1981) identified as more appropriate gravel mining sites because of their tendency toward deposition. Thus, any increased channel capacity from mining is likely to persist only a short time, until redeposition. As redeposition occurs, downstream reaches may be starved of sediment.

Figure 43. Right bank levee on Dungeness River, about 360 m (1200 ft) upstream of Hwy 101 (Photograph by Kondolf 2001).

View upstream showing private home constructed on former active channel at approximately the same elevation as the currently active channel.

Moreover, flood elevations in a reach are controlled primarily by downstream hydraulic controls, such as constrictions or drops. In reaches with strong downstream controls (such as upstream of bridge constrictions), the roughness or elevation of the bed may be irrelevant, as the channel is filled with ponded water above the constriction during high flows. In such cases, gravel extraction would have no effect on flood elevations.

Gravel extraction and channel cleaning for flood control could be expected to have similar results to other channelization projects. By speeding velocities and lowering flood stage in the local project reach, peak flows are no longer attenuated in the project reach, and downstream flood peaks are thereby increased.

In our literature review, the only published study on the potential flood control benefits of instream gravel mining, besides the rather specific case of the Wamakariri River (Griffiths 1979) was Prych (1988), who inferred the mining had locally prevented aggradation of 0.12 m (0.4 ft) and thereby preserved flood capacity of the White, Carbon, and Puyallup Rivers. However, his inference of flood control benefits was weak in that he lacked any direct evidence of channel change, and even a change in rate of aggradation would not necessarily have a comparable effect on hydraulic profile. Collins (1991) documented total 1972-1991 bed degradation in a 11 km-long (6.9 mi) reach beginning 0.6 km (0.4 mi) upstream from the mouth of the Pilchuck River reach was equivalent to about 6,100 cubic meters/year (8,000 cubic yards/year). During the same period, about 11,500 cubic meters/year (15,000 cubic yards/year) were removed from the reach by bar scalping and in-channel pit mining during the same period, and about 35,000 cubic meters/year (46,000 cubic yards/year) in 1969-1971. The average channel bed incision in the reach was 0.5 m (1.5 ft) during the same period. Because annual average gravel extraction was greater than actual bed degradation, the incision and potential flood control benefits have been partially attributed to gravel extraction. However, Collins (1991) neither measured flood control benefits, nor directly attributed potential benefits to gravel extraction.

The Dungeness River (drainage area approximately 500 km^2 (200 mi^2)) leaves a narrow, confined valley about 450 m (1500 ft) south of Hwy 101 (southwest of Sequim) and flows northward across its alluvial fan/delta to its mouth in the Strait of Juan de Fuca. Channel gradients are steep (about one percent) and, as typical of rivers leaving confined valleys into unconstrained, low gradient settings, the Dungeness actively deposits coarse sediment and naturally was characterized by frequent channel shifts. Levees protecting human settlement on former active channel surfaces have confined the river in reaches that would naturally be highly dynamic (Figure 43). Northwest Hydraulics Consultants (NHC) (1987) reported aggradation rates of 52 mm/y (0.17 ft/yr) and recommend gravel mining within the active channel outside the low flow channel. NHC further recommended that 19,100-m^3 (25,000-yd^3) mines be excavated as long trenches (parallel with flow direction) at two sites (about 0.8 km (0.5 mi) upstream and 2.4 km (1.5 mi) downstream of Hwy 101). These elongated mines would be designed to capture the river's main flow during winter high flows, and NHC predicted they would produce degradation of over 0.15 m (0.5 ft) over a distance of 4.8 kilometers (3 mi).

Although some such "trench" mines were excavated, we did not find a follow-up study published reporting the exact locations or amounts. However, the US Bureau of Reclamation (USBR) has conducted an analysis that indicates the aggradation (most pronounced in reaches confined by levees) is unlikely to continue in the absence of further mining, and that long-term gravel mining is probably not needed except if levees are set back, in which case the mining would be needed to locally restore predisturbance channel gradients and allow the river to continue flowing in its present course (otherwise avulsion would be likely) (T. Randle, US Bureau of Reclamation, Denver, personal communication. 2001). The USBR report was originally due in September 2001 but has been held up by funding issues. Once published, the Dungeness River case should provide a useful example of gravel mining used for flood control, especially if it reports specific locations and amounts.

Evaluating Benefits of Gravel Removal for Flood Control

King County is now systematically evaluating the potential for instream extraction to increase channel capacity at several King County sites. Using five sites on the Snoqualmie River system, King County is applying the HEC-RAS model (a fixed bed, step backwater hydraulic model) to model water surface elevations for various bar-scalping scenarios, comparing results to existing conditions, uniform channel dredging, and levee setbacks (T. Butler, King County, personal communication 2001). The model is static, in that it models flow under the post-mining condition and does not account for channel changes over time in response to the modified channel geometry or to the removal of material from the system.

It is difficult to quantitatively evaluate the effects of instream extraction of flood elevations. There are a number of problems with modeling flood elevations, such as specification of roughness coefficient, the effects of sediment transport on flow, potential changes in channel cross section during the flood (temporary scour and long-term aggradation or incision), and superposition of water surface at bends. Thus to accurately model water surface elevations in floods requires calibration with observed water surface and discharge measurements. Uncertainties about the rate at which extraction sites refill with sediment pose other, specific problems for modeling the effects of extraction. A number of sites proposed for gravel extraction for flood control are in local depositional reaches (such as the Tolt and Raging Rivers above their confluences with the Snoqualmie), and sites of extraction may be quickly refilled such that the preproject channel geometry used in the model may not be accurate during the flood.

One fundamental problem with modeling flood capacity effects of instream mining is that the widely used static models such as HEC-2 or HEC-RAS cannot predict channel shape over time because the cross sections are static model inputs, so must assume an unchanging channel shape – despite the fact that we know the channel form will change in response to gravel extraction and subsequent channel erosion and deposition during floods.

To adequately evaluate the potential effects of extraction on flood levels requires an analysis that considers not only changes from extraction at the cross section, but also influences of downstream hydraulic controls and potential rates of redeposition and evolution of the channel to the modified sediment regime. Thus, if gravel extraction is proposed to reduce flood hazard, the justification for the action should logically include first specification of a flood control reduction goal, estimates of bedload sediment transport into the reach (including recognition of inter-annual variability), probable rates of deposition within the extraction site, and a consequent proposed removal rate. Given experience elsewhere that gravel extraction can have side effects that increase flood risk such as incision and channel instability (Soil & Water 1985), the potential environmental effects of the extraction should be fully analyzed, and future changes in channel form monitored precisely enough so that future removal rates can be adjusted based on observed channel response (Figure 44).

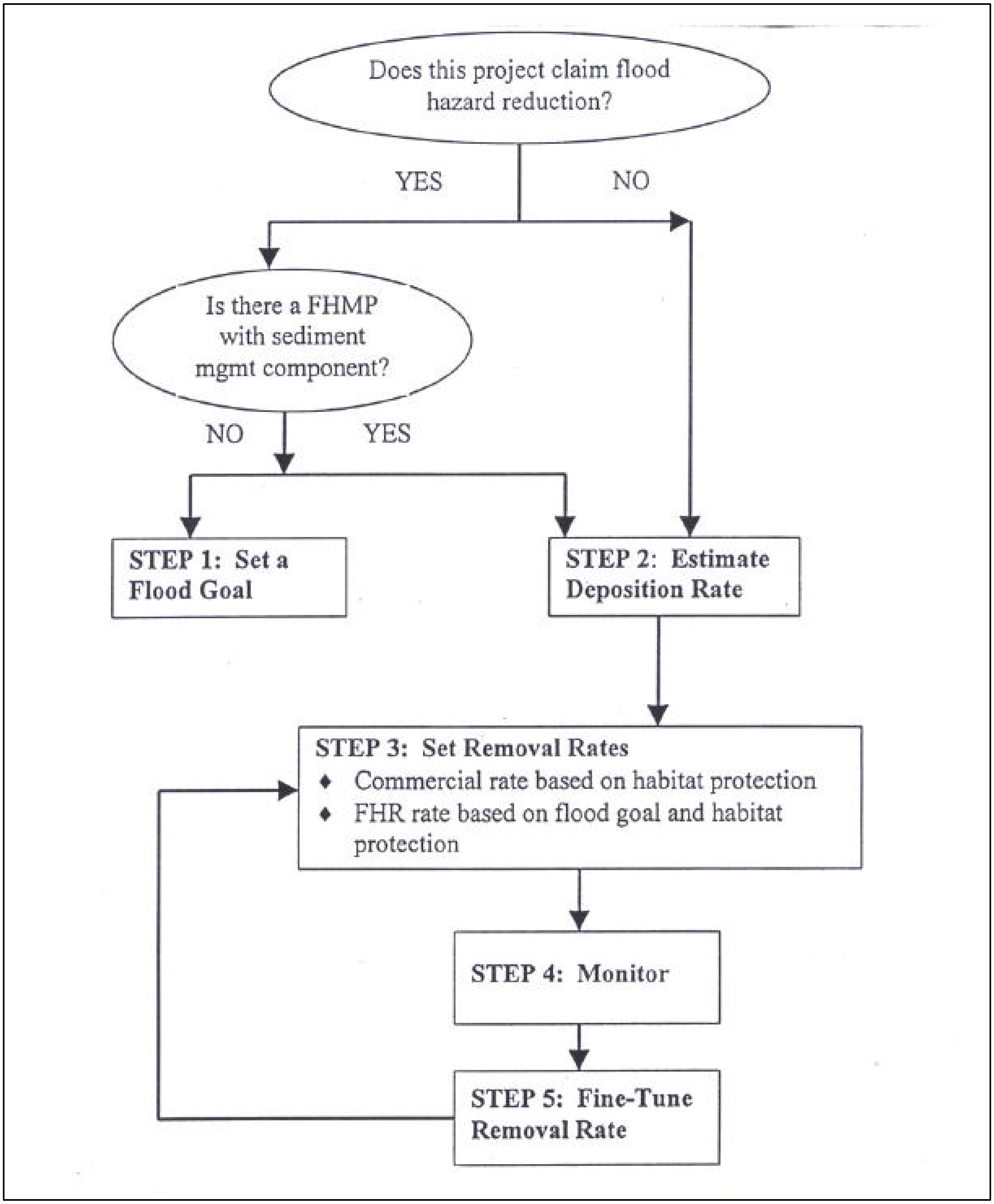

Figure 44. Flow chart of process to analyze and plan gravel extraction for flood control. FHMP is "flood hazard management plan" (Source: WDFW 1996).

In addition to evaluating the potential effects of in-channel mining to increase flood capacity, analysis of alternative approaches is required under NEPA and therefore by the USACE in the CWA Sec 404 permit process. Alternatives to dredging and levee raising include removal of sections of levees to provide alternative flood routes and channel and floodplain storage, as well as non-structural alternations such as elevations of existing structures and land-use regulations.

Case Study: Big Quilcene River

The Big Quilcene River drains 180 km^2 (69 mi^2) on the east slopes of the Olympic Peninsula. A combination of small ca. 1500 m^3 (2,000 yd^3) gravel traps in bars and levee removal and set back have been employed to reduce the likelihood of flooding and channel avulsion in lower reaches of the river, which constitute a natural deposition zone. Collins (1993) documented thalweg aggradation of about 0.6 m (2 ft) from 1971-1993, for an annual average aggradation rate of approximately 1200 m^3/km/yr (1,000 yd^3/mi/yr). Williams et al. (1995) obtained a similar value from delta progradation from 1947-1990. Development on the floodplains bordering the river is threatened by flooding and channel erosion, especially as the bed aggrades over time. Williams et al. (1995) proposed levee setbacks and lowering to reduce flood risk while minimizing impacts on salmon habitat. The proposed actions under the Alternative 4 of Williams et al. (1995) are shown in Figure 45 along with the measures actually implemented as of August 2001.

In addition to removing nearly 600 m (2,000 ft) of the downstream-most section of left bank levee in 1995 and removing two flood-prone houses along the left bank 180-540 m (600-900 ft) downstream of the Linger Longer Bridge, Jefferson County has operated three gravel traps in gravel bars (Figure 45). The traps are excavations within gravel bars at sites selected for local hydraulics that would tend to recreate the bar forms (Al Latham, Jefferson County Conservation District, Port Hadlock, and Dave Ward, Jefferson County Public Works, Quilcene, personal communication. 2001). For example, the upstream trap is located in a small expansion downstream of a protected reach of bank that protrudes into the channel and creates a secondary circulation cell along the right bank. The two downstream traps are located together on a large left-bank gravel bar downstream of a gentle leftward bend in the channel (Figure 46).

The traps are excavated until the sides collapse, typically 2.0-2.5 m (6-8 ft) deep. They are about 36-85 m (120-140 ft) long, and a minimum of 3 m (10 ft) from the low-flow channel. At the downstream end of the excavation, an egress channel is dug to connect the excavation to the river to avoid trapping fish. The traps have been excavated in 1993 and annually from 1995-2000 with an average total of 1800 m^3 (2,000 yd^3) excavated from all three traps. Due to the lack of high flows and sediment transport, the traps did not fill in 2001 and thus were not excavated in 2001 (Dave Ward, personal communication. 2001).

Cross sections surveyed by Al Latham (Jefferson County Conservation District) have shown continued aggradation (of about 1 m (3 ft) at the thalweg) downstream in the delta at XS 03+28 (Figure 47), and minor aggradation immediately downstream of the two downstream traps (shown in Figure 46) at XS 14+10, located about 590 m (1900 ft) downstream of Linger Longer Bridge (Figure 48).

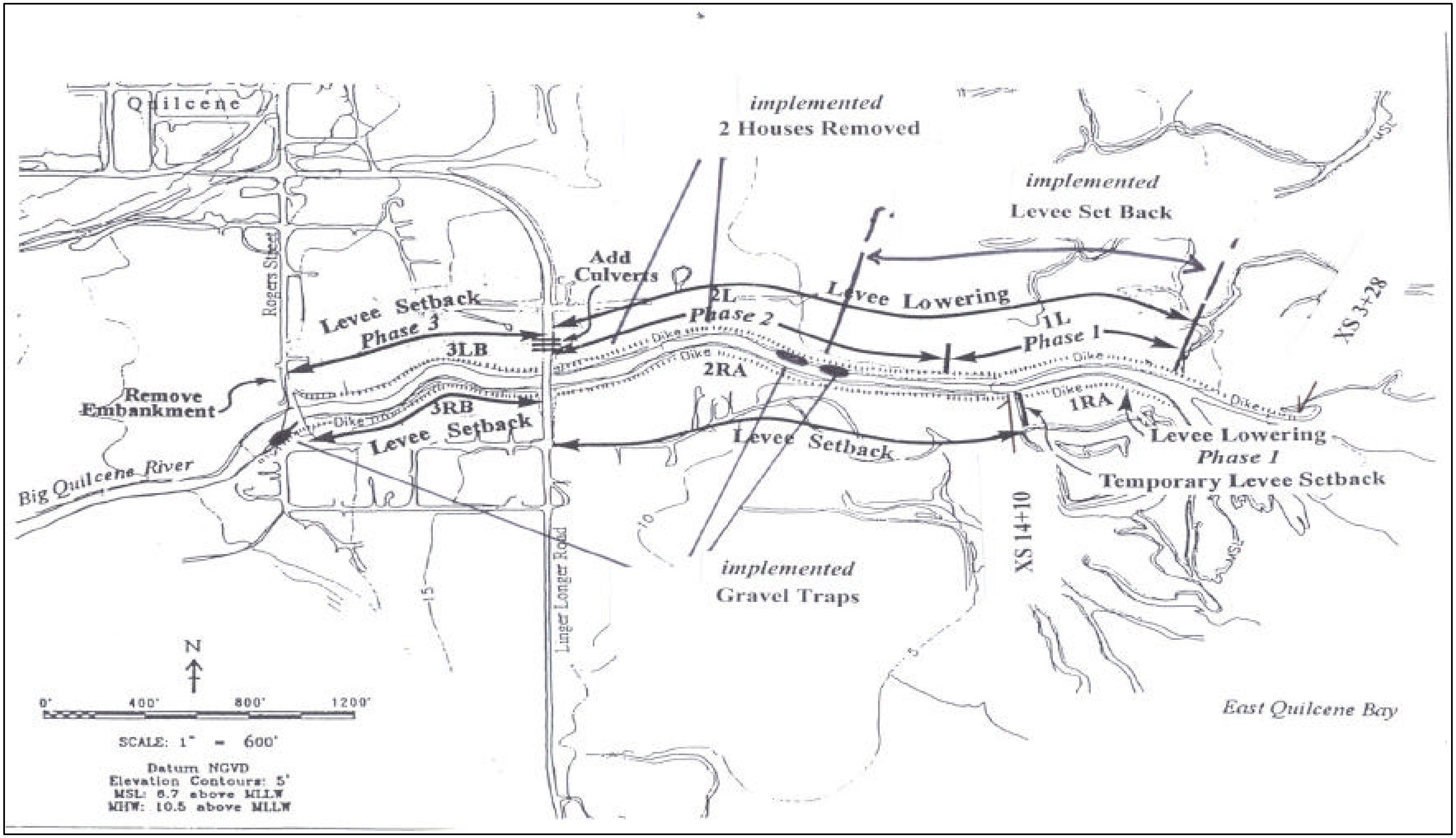

Figure 45. Flood management actions on the Big Quilcene River, as proposed by Williams et al. (1995), and as actually implemented to date.

Implemented actions identified as such. Adapted from Williams et al. (1995). Locations of recent actions from Dave Ward, Jefferson County Public Works. (Personal communication 2001).

Figure 46. View downstream to gravel trap in a left bank gravel bar on the Big Quilcene River (Photograph by Kondolf 2001).

What can be learned from the experience on the Big Quilcene River to date? We are fortunate to have excellent cross-section surveys documenting channel change since 1994. However, it is difficult to isolate the effects of the gravel traps from the effects of the levee set back, as both occurred in the same time frame. However, it appears that the gravel traps have probably not damaged fish habitat based on (1) the cross section survey results showing continued (albeit minor) aggradation, and (2) the small scale and careful placement and design of the traps.

The county intends to acquire additional flood-prone properties along the lower river when and if property owners desire to sell in the future. Once the needed properties are obtained, the Linger Longer Bridge will be extended in the left bank direction (i.e. the earthen berm will be replaced by an open bridge that does not restrict and block flood flows) and dikes set back, in accordance with approved plans (Ken Cook, formerly with Jefferson County, personal communication to Ken Bates, 2001). This will permit flood flows to spread out naturally over the floodplain/delta and permit more natural channel processes to operate, thereby creating more diverse and natural habitats for salmon without conflicting with human settlement. Once these changes are made, it is likely that the gravel traps will no longer be used. Funding for the next phases of the Big Quilcene program (acquisition of properties and levee set back) should be a statewide priority, given the importance of the fish runs here and the opportunity to solve a flood problem and enhance habitat simultaneously through levee setbacks and restoration of natural fluvial processes.

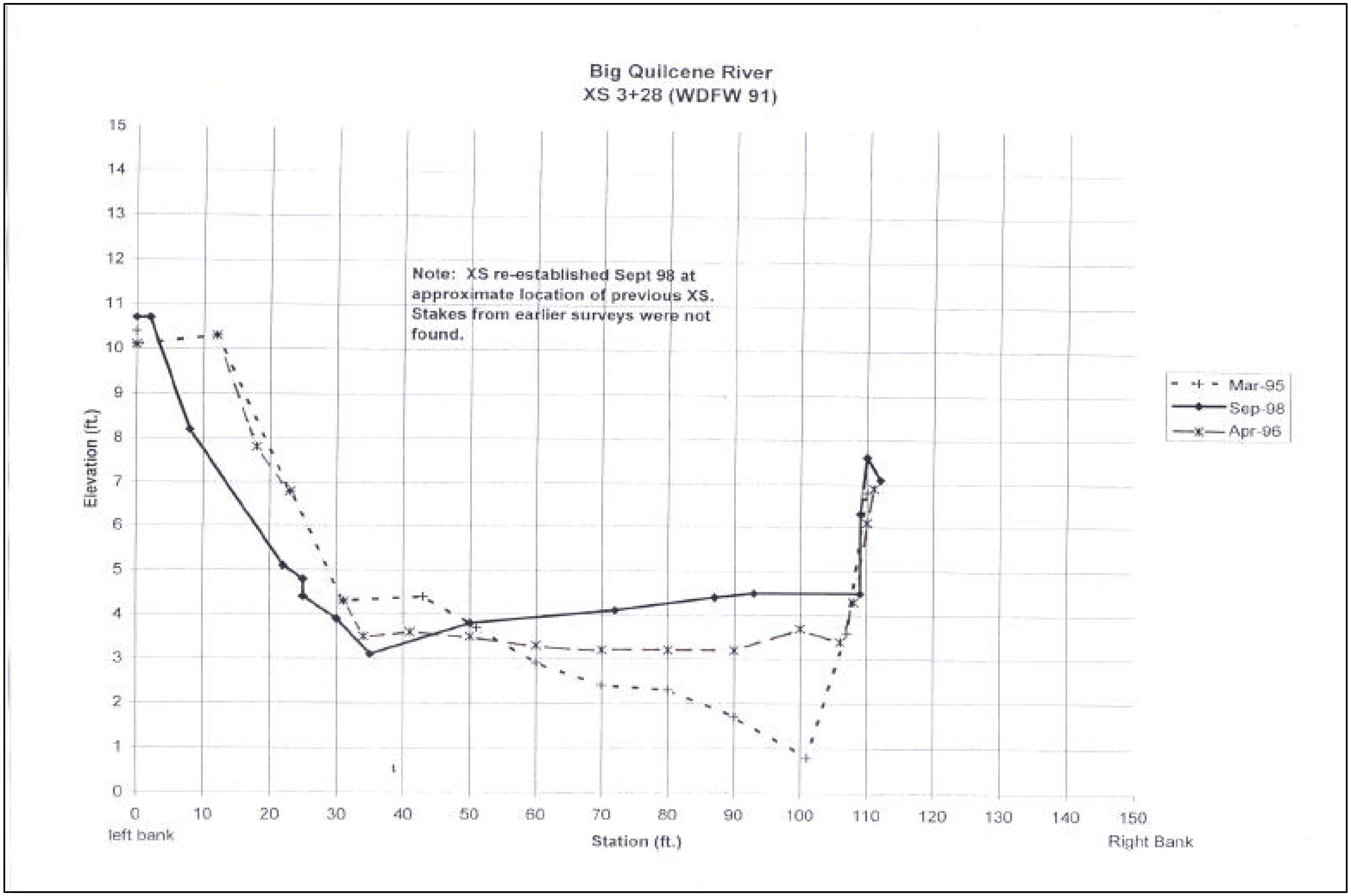

Figure 47. Sequential cross sections of the Big Quilcene River at station 03+28 about 50 m (160 ft) upstream of its mouth (Source: Jefferson County Conservation District, unpublished data).

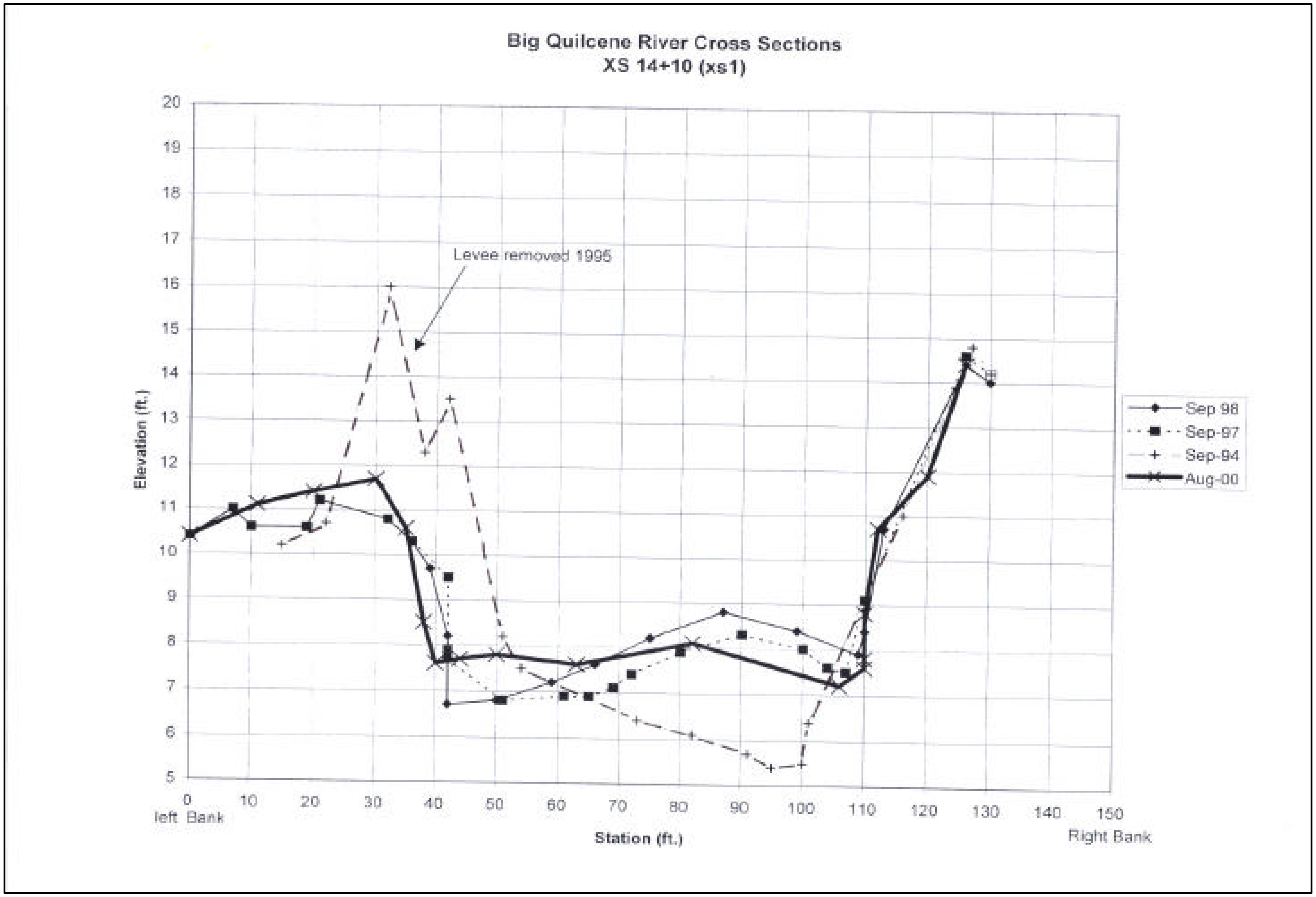

Figure 48. Sequential cross sections of the Big Quilcene River at station 014+10 about 590 m (1900 ft) downstream of Linger Longer Rd., showing left bank levee removed in 1995 (Source: Jefferson County Conservation District, unpublished data).

Minor bed aggradation has occurred since 1994 despite the excavation of two gravel traps just upstream annually from 1995-2000.

Management, Reclamation, and Restoration of Floodplain Pits

Reclamation to Off-Channel Spawning and Rearing Habitat

Floodplain gravel pits have been successfully developed as off-channel spawning and rearing habitat for salmon and trout in Idaho (Richard et al. 1992) and on the Olympic Peninsula (Partee and Samuelson 1993). Such habitats are more likely to be successful to the extent that their geometries resemble natural side channels (typically groundwater-fed), which are used for spawning by salmonids in western Canada and Alaska (e.g., Vining et al. 1985). For spawning habitat, extractions should be linear, relatively narrow and shallow to create flowing water conditions. For rearing habitat, deeper pools may be appropriate. The WEYCO-Briscoe ponds along the Wynoochee River, Washington, were created by extractions that maximized habitat quality upon reclamation rather than maximizing extraction of aggregate from the site (Partee and Samuelson 1993). One result of this was that a limited amount of material was removed; the resulting ponds are shallow and complex. Off-channel habitat such as this is unlikely to be beneficial for salmon in areas with warmer summers because the off-channel ponds are likely to provide habitat for warm-water species that prey upon salmon smolts.

Norman et al. (1998) reviewed techniques for establishing off-channel salmonid habitat in reclaimed gravel pit lakes on the Wynoochee, Humptulips, and Yakima Rivers, and concluded that success of converting gravel pit lakes to off-channel salmonid habitat depends on having good access for fish to leave and enter the main channel, low risk of pit capture, flooding or drought, and adequate cover, food supply, and water quality. Smaller, shallower pits that are closer in scale to the adjacent river are generally more successful, as also recommended by Collins (1997).

Cederholm and Scarlett (1991) blasted a series of ponds to form a “beaded” off-channel habitat configuration on Swamp Creek, Clearwater River Basin, Olympic Peninsula, as an experiment to improve the survival and growth of overwintering juvenile coho salmon in ephemeral wall-base channel streams. The overwinter survival of branded juvenile coho entering the beaded channel increased from zero before enhancement to 43% in 1986-1987 to 70% in 1987-1988. Frequent spring rains in the Pacific Northwest generally allow for sufficient runoff for smolts to escape back to the main channel, making beaded channel construction a viable habitat improvement technique.

On the Clearwater River, Olympic Peninsula, Washington, Peterson (1982) documented immigration of 9,530 juvenile coho salmon into two riverine ponds, over 85% during October and November freshets. Abandonment of summer rearing sites and lengthy relocation to ponds illustrates the necessity of widely separated and diverse habitats in the freshwater production of coho salmon. Protection of summer rearing habitat alone may not be enough to protect overall fish production, as the fish may depend on totally separate habitat at a later season.

Jenks (1989) reviewed existing and potential off-channel pond rehabilitation projects on the North Fork Stillaguamish River, and documented observations of juvenile coho salmon immigration into small groundwater-fed tributaries during fall and early winter freshets.

In the Yankee Fork, Salmon River, Idaho, channels were excavated to connect gravel pits to the Yankee Fork, with adjustable weirs at the downstream end of most ponds (Richards et al 1992). Dissolved oxygen, water temperature, conductivity, and turbidity were found to be within ranges suitable for juvenile chinook salmon, and the fish were observed to use all available habitats (1.6 hectares (4 ac) of open-water pit and 610 m (2000 ft) of channel), preferring channels with cover the most and open water the least.

Bayley and Baker (2000) sampled native and exotic fish populations in two floodplain gravel pits (14.5 and 2 hectares (36 and 5 ac), both over 7.6 m (25 ft deep) and the adjacent (connected) channel of the Willamette River, Oregon, in 1998 and 1999, to estimate restoration potential. Water temperatures were as high as 24.8°C (76.6°F), and the proportion of exotic fishes was higher in the gravel pits than in the Willamette River and its alcoves in the summer. In winter during floodplain inundation, native fishes were found in higher abundance on floodplain sites other than gravel pits.

In summary, off-channel gravel extraction can be designed to provide spawning and rearing habitat provided the excavations are shallow, irregular, and elongated in form, and provided that water temperatures remain cool. Deep pits provide little salmonid habitat (favoring exotics instead), and where summer temperatures are high (in California, Oregon, and perhaps Washington east of the Cascades) water temperatures in the pits will tend to warm up, supporting exotic warm-water species that prey upon salmon smolts.

Reclamation to Other Uses

Dry pits can be reclaimed to agriculture, as is done at the Aspen Mine, which exploits older terrace gravels of the American River southeast of Sacramento. The gravel is removed, the topsoil replaced, and the resulting ground surface (presently used for agriculture) is about 6 m lower than the original surface (Sacramento County 1987). On wet pits, reclamation to agriculture is not possible unless the pit is refilled so the resulting land surface is above the water table. In the Aggregate Resource Management Plan adopted in 1980, Sonoma County, California, intended to direct floodwaters into floodplain gravel pits along the Russian River, so the pits would refill from deposition of sediment. However, the California Department of Fish and Game prohibited flood waters from being directed into the pits because of the potential for fish to be carried or swim into the pits, only to become trapped as floodwaters receded (Marcus 1992). Moreover, the time required for such refilling by sediment could be quite long, depending upon the river's sediment load and caliber, and the hydraulic conditions at the approach and entrance to the pit. The sediment deposited in the pit from suspension (sand and silt) would be considerably finer than the gravel and sand removed, thereby affecting groundwater flow patterns by creating lenses of reduced hydraulic conductivity within the wider floodplain aquifer of high conductivity gravels.

The pit could be refilled with other materials. However, to preserve the hydraulic conductivity of the aquifer medium would require filling the pit with something like gravel and sand. Abandoned gravel pits have been utilized as landfills in some areas, but it is difficult to imagine a less favorable site environmentally for a landfill than a floodplain gravel pit, with its high water table, the high hydraulic conductivity of the floodplain gravels, and the resultant threat posed to water supply and aquatic ecological resources.

If the pits are not refilled, they can be used for swimming, as is done in Helena, Montana, and Santa Clara Valley, California, and along the Yakima River near the confluence of Manastash Creek near Ellensburg, or for boating and water skiing, as in the Hedeland district of Denmark (Schultz 1990). Pits can also be used to recharge groundwater, especially in proximal alluvial fan settings, when flows are diverted into the pits, as done along Alameda Creek, Fremont, and Stevens Creek, San Jose, both in California.

Increasingly, reclaimed gravel pits are being used provide riparian wetland habitat, thereby partly mitigating historical losses of wetland habitat as high as 91% in western North America since the mid-19th century (NRC 1992). The potential of former pits as wildlife habitat was emphasized in a recent publication of the aggregate industry in California (CVRSGA 1995): "There is a satisfying symmetry between sand and gravel mining and wetlands reclamation, a balance between the development of one resource (construction aggregates) and the creation of a new resource (wetlands)."

Lacy (1996) examined issues in reclaiming surface sand and gravel mines to waterfowl habitat and found that complex features such as irregular shorelines, varying depths, native food and cover plants, gently sloping banks, and islands were features necessary for most waterfowl. Research on habitat values of abandoned gravel pits in the UK has identified shallow waters (< 1m) and gently sloping banks as providing the most productive habitat because sunlight can penetrate to the bottom in shallow waters, supporting growth of aquatic macrophytes, and emergent banks with shallow water tables can support wetland plants (Andrews and Kinsman 1990, Giles 1992). The plants provide habitat and food for aquatic and riparian species. Andrews and Kinsman (1990) recommended that pit margins be sloped at 7% or less over at least 20 m (65 ft) (measured normal to the shoreline) to provide a minimum of 15 m (50 ft) of water < 1 m (3.3 ft) deep even with seasonal water table fluctuations of 0.3 m (1 ft). As an alternative to sloping banks, benches can be cut in the pit margins to provide both shallow aquatic habitat and exposed surfaces for establishment of riparian vegetation (Baseline Environmental Consulting 1992). While waterfowl require some open water (consistent with deeper waters in pits), observations suggest that waterfowl avoid swimming near steeply sloping banks because of the threat posed by terrestrial predators that may lurk directly above the waters along a steep bank (Tom Griggs, The Nature Conservancy, Hamilton City, California, personal communication 1995).

Steeply sloping banks on gravel pits can also pose safety risks, as humans and animals may not be able to exit a pit due to the steepness and loose material of the banks.

Despite the importance of these shallow water marginal habitats, most gravel pits presently abandoned on the landscape have steeply sloping banks, providing only a narrow band along which riparian vegetation can establish in between deep waters and steep, thistle-covered uplands. A deep, steep-sided pit maximizes the aggregate production from a given area. To create gently-sloping or stepped banks requires either enlarging the area of disturbance (to maintain the same yield of aggregate) or reducing the aggregate yield (to maintain the same area of ground disturbance).

Water table fluctuations pose another constraint upon creation of shallow water habitat. The Andrews and Kinsman (1990) recommendation of a 20 m (65 ft) wide sloping bank is based on an assumed water level fluctuation of 0.3 m (1 ft), a value that may be typical of humid climates with relatively uniform seasonal distribution of precipitation and perennial streamflow. However, in more hydrologically variable climates, river stage and alluvial water level fluctuations are typically greater, with the most extreme fluctuations along intermittent streams, where establishing riparian vegetation may be impossible without irrigation.

Isolation of Captured Floodplain Pits

Captured floodplain pits have been identified as a principal factor limiting recovery of chinook salmon populations in the Sacramento and San Joaquin River system in California. To reduce predation of juvenile salmonids by exotic warm-water species that thrive in the pits, a number of projects to isolate gravel pits have been proposed or implemented to date. To eliminate predation by exotic warmwater fish, the pits must be filled completely, or partially filled, with the fill portion used to separate the part of the pit remaining as open-water. As noted earlier, to preserve the hydraulic conductivity of the aquifer medium requires filling the pit with something like gravel and sand, which may need to be derived from a mine elsewhere, or, in the examples below along the Tuolumne and Merced Rivers and Clear Creek in California, gold dredger tailings have been used.

Pit isolation projects have received funding from major restoration programs in California, notably the Calfed Bay-Delta Ecosystem Restoration Program (Calfed) and the US Fish and Wildlife Service (USFWS) Anadromous Fish Restoration Program (AFRP) authorized by US Congress under the Central Valley Project Improvement Act of 1992. The projects funded to date by Calfed are reviewed below, based on review of documents and information from Mike Fainter (Calfed staff, personal communication 2001). This list is not complete in terms of cost, and does not include all such projects, as some pit isolation projects did not receive Calfed funding and thus would not appear in this brief review. Nonetheless, the available figures can suggest the typical costs of refilling abandoned gravel pits to reduce predation on juvenile salmonids.

On the Tuolumne River, a project to isolate a captured gravel pit designated as Special Run Pool (SRP 9) was authorized at an initial cost of $2.35 million in 1997 from Calfed, and received additional funds from AFRP. Implementation was delayed until summer 2001 due in part to cost overruns: the unit price of gravel sharply increased as a result of many such restoration projects creating a demand for dredger tailings, permitting the owners of these formerly virtually worthless deposits to demand higher prices. Also on the Tuolumne River, Special Run Pool (SRP) 10 has been funded (in fiscal year 2001) for over $540,000 from Calfed for planning, permitting, and engineering design, but has not yet been funded for implementation. In the reach of most active former in-channel and current floodplain pit mining, the so-called "7-11 Mining Reach," nearly $3 million was allocated in fiscal year 1997 (as part of a cost-share with AFRP), with implementation set for summer 2001. Also in the reach of most active gravel mining, the M.J. Ruddy Mining Reach Project was funded at about $1.36 million by Calfed in fiscal year 1998, but this project is evidently not yet built.

On the Merced River, Calfed provided about 1.6 million (1999) to partially fill and isolate the Ratzlaff gravel pit. Approximately another $2 million was provided to this project from a fund designed to mitigate post-1986 increased fish kills at the Sacramento Delta water diversion pumps, and an additional $250,000 was contributed from AFRP, making the total cost around $4 million to isolate this pit. In the Robinson Reach of the Merced River, Calfed initially provided $2.43 million in 1998 and an additional $1.7 million in 2001 to isolate a gravel pit.

On Clear Creek, a project to fill in former gravel pits and recreate a channel in a reach completely reworked and pockmarked by gravel mining has been funded at over $3.56 million (1998) by Calfed. Implementation is about half completed to date, the remainder expected by end of fall 2001.

The actual costs of isolating gravel pits will depend, of course, upon the surface area extent, excavation depth, and geometry of the pit and channel, as well as the availability and cost of suitable fill material. Experience to date in the Central Valley of California suggests that the costs of isolating gravel pits to reduce predation to date have been around $3-4 million per pit, although all these projects use dredger tailings available nearby. The figures for isolating pits elsewhere are not likely to be much less, unless the pits are smaller and a comparable source of fill material is available. We can at least conclude from this review that pit isolation is a costly exercise, and given the likelihood of pit capture, these costs of “decommissioning” should probably be taken into consideration when permits for the gravel pits are initially awarded. It would be an interesting exercise to estimate the value of gravel extracted from these pits during their period of commercial operations compared to the current costs of reclamation.

Data Gaps

Despite the considerable increase in understanding of fluvial geomorphology and aquatic and riparian ecology in recent decades, there are still relatively few studies directly addressing the impacts of gravel mining in its various forms and the potential for restoration of ecological integrity after mining. Most of better documented studies of geomorphic effects of mining have involved large extraction rates over a decade or more, resulting in large, measurable changes in channel form, changes that are large enough to be clearly detected despite the inherent noisiness of the fluvial system. Studies have documented direct ecological effects of fine sediment from mines, but the longer-term, indirect and cumulative effects of mining up the food chain and over time are harder to study, and have not really been tackled. To study site–specific effects of instream mining would require careful measurement of mining-induced changes to baseline conditions, yet baseline conditions have generally not been documented prior to mining, at least at the level required to detect future change. Given that new instream mines are unlikely to be approved in Washington, we are unlikely to see a before-and-after study with such baseline data. Nonetheless, field-based case studies could shed light on the effects of mining on sediment transport, channel form, and riparian aquatic habitat. Experimental gravel bar scalping was undertaken in March 2000 on the Fraser River, BC, under physical conditions similar to those in Washington State rivers and with similar aquatic resources. Response to the extraction is being monitored by University of British Columbia professor Mike Church, his students, and colleagues.

Quantitative site assessments should be performed to measure and document habitat changes and habitat use and preferences of salmonids before and after bar scalping activities using both scalped and control sites. Excellent studies published by Pauley et al. (1989) and Weigand (1991) provide quantitative before-and-after assessments of loss of habitat preferred by salmonids on the Carbon, White, and Puyallup rivers following bar scalping activities in 1988 and 1990. Similar studies should be completed on additional rivers to document effects of ongoing bar scalping activities.

Better (and more reliable data) on current and historical extraction rates are needed to understand the magnitude and timing of the "forcing function" that has induced many of the changes observed. However, mining production data are treated as proprietary information, and extraction rates are generally not considered public information, except when aggregated by counties or larger units, despite the public interest in the floodplain and public ownership of the channel.

Hyporheic zone impacts of gravel mining, both instream and floodplain pit, are essentially undocumented. The Yakima River study now underway by Flathead Lake Biological Station should yield some useful data, but it will be only a start. Moreover, effects of instream mining on hyporheic zones can only be inferred now based on considerations such as reduced gravel thickness and extent.

Food web impacts of gravel mining are not well understood. Predation on juvenile salmon by introduced warm water species (that thrive in the artificial habitats created by floodplain pits) has been documented in California, but no such studies have been undertaken in Washington. The food-web implications of disrupting or eliminating shallow gravel riffle habitats and reducing abundance of large woody debris in the channel through instream mining have not been directly measured in the field, nor even fully explored in theory.

Bed coarsening as a result of instream gravel mining has rarely been studied. Again, lack of baseline data is a key limitation, though sometimes pre-disturbance bed material size can be inferred (within a range) if the site was formerly used by spawning salmonids but is no longer due to excessively coarse substrate. The efficacy of movable bed hydraulic models to predict coarsening (and other bed changes) in response to gravel mining deserves study and testing.

Straightening and dredging of drainage channels for agriculture is widespread throughout the state, but remains essentially undocumented in extent or impacts.

Conclusions

Awareness of the impacts of gravel mining on rivers has increased dramatically in recent years. but good data sets documenting the physical and ecological effects are rare. Washington actually has some of the best studies of gravel mine impacts of any state, notably Collins and Dunnes' (1986) analyses of the Humptulips, Wynoochee, and Satsop rivers, and Collins' studies of the Pilchuck (1991), the Big Quilcene (1993), and Stillaguamish (1997). These studies have relied on historical analyses of watershed and channel conditions to develop sediment budgets (thereby quantifying amounts of over-extraction) and to measure channel incision and other changes attributable to the extraction and resultant sediment starvation.

The effects of multiple small-scale mines and of bar-scalping are commonly viewed as less damaging than large-scale mining, but their effects can be significant. "Relieving pressure" on the outside bend is often cited as a benefit of bar scalping, but eliminating the bar changes the flow hydraulics, and straightening the high flow path may increase gradient and induce incision. Removing the bar head (a hydraulic control) can affect water surface elevations and bed stability upstream, washing out gravels at a lower discharge. As the scalped bars aggrade, they store sediment and deprive downstream reaches of gravel supply.

The potential of gravel mining to stabilize the channel is a hotly–debated topic in Washington, but it is not directly addressed in the scientific literature. The experience along the Big Quilcene River suggests that gravel traps can be utilized to trap a portion of the sediment load on an aggrading reach without negatively affecting channel form, but recent reductions in flooding along that river are probably mostly due to the levee setback done at the same time. Reports of instability caused by instream mining or capture of floodplain pits, suggests that while gravel mining may have a role in stabilizing aggrading rivers, in most rivers, mining is probably more likely to destabilize through incision and undercutting of banks. Likewise, on channels bounded by rip-rapped levees, dredging may be needed to maintain channel capacity in aggrading reaches, but the underlying problem is the riprap approach to river management, which is not sustainable without massive intervention such as gravel extraction and resultant loss of habitat, as observed on the Walla-Walla River.

Bedload traps offer considerable potential as sources of aggregate with minimal impacts. They are currently employed upstream of reaches in which aggradation is a concern, such as upstream of highway bridges crossing alluvial fan streams. Advantages include the possibility to limit direct impacts of extractions to specified sites and to build good access that avoids damage to riparian habitats, and the possibility to construct grade control structures that prevent upstream headcut migration. Issues include the potential for the grade control to act as a barrier to fish migration or for the deposits within the gravel trap to result in very shallow depths and thereby act as a barrier to migration, and the downstream consequences of taking bedload sediment out of the system.

Moreover, the effect of the gravel types is beneficial only when there is really a problem of bedload sediment downstream. Otherwise, negative effects of sediment starvation may result.

Floodplain pits that remain isolated from the active channel have largely undocumented effects on groundwater flow, and usually confine the channel with rocked levees. Once breached, they trigger channel incision upstream and downstream, lead to loss of habitat, and provide habitat for exotic species that prey on salmon. If summer water temperatures remain cold enough, and if excavations are sufficiently shallow, linear, and irregular in form, off-channel extractions have the potential to serve as artificial side-channel habitats for spawning and juvenile rearing. In Washington, there have been some successes with these on the Olympic Peninsula, but elsewhere higher summer temperatures may make such extractions serve mainly as habitat for exotic warm-water fish that prey upon juvenile salmon a phenomenon documented as a principal source of mortality for juvenile salmon in California. Thus, there is potential, but not everywhere, and this practice should probably be approached cautiously in any event lest the "enhancement" serve the wrong species, such as large-mouth bass rather than salmonids. Floodplain pits can be viewed as a substantial liability for future generations, either to maintain their separation from the current channel, or if already breached, to suffer consequences of resultant channel incision, predation losses on juvenile salmon (if salmon still exist), or to pay the price of re-isolating the breached pits.

The cumulative effects of gravel mining over time and upstream/downstream, and the cumulative effects of multiple mines on one river system, have rarely been addressed. As discussed above, the real impacts of gravel mining are cumulative – additive effects of extractions on the sediment budget, increasing extent of floodplain pits, multiple captured pits, etc.

Future management of gravel mining should emphasize incentives to use alternative sources of construction aggregate, such as glacial outwash deposits, reservoir deltas, quarries, and recycled concrete rubble. Except for outwash deposits where they exist, at present there is little incentive to use these alternate sources, as they generally require greater transport or processing than gravel taken from channels and floodplains. Given that the full costs of extracting from rivers are not incorporated in the price paid for the product, it will be difficult to encourage use of these alternatives when, in effect, extraction of river gravels is subsidized. The cost of mining-induced infrastructure damage has shown to be equivalent of $2.70/tonnes ($3/ton) of gravel produced in a California river (Harvey and Smith 1998). If these infrastructure costs were incorporated into the price of this gravel, the river-run gravel would look less economically attractive and alternatives might look better than at present.

Acknowledgements

This report was greatly improved by review comments on early drafts from Tim Hilliard, Jim Park, Al Wald, James Anthony, Rob Shanz, and Jim Park of WDOT; Ken Bates of WDFW; Dave Norman of WDNR; Terry Butler of King County; and Doug Pineo, WDOE.

We also received useful comments on report scope and suggestions for data sources from participants at a workshop in November 2000, including Perry Harvester, Dan Nauer, Terry Butler, Tim D'Acci, Gordy Zillges, Dave Norman, Jeff McGowan, Marion Carey, Mike Chamblin, Bruce Heiner, Julie Nelson, Michelle Cramer, and Paul LaRiviere. Neil Rickard, WDFW, and Doug Canning, WDOE, also provided useful comments during the workshop's summary session.

The authors would like to thank Perry Harvester, Paul LaRiviere, and Brent Renfrow, WDFW, for coordinating informative field visits to gravel mining and navigational dredging sites in the Yakima and Snake River systems. Doug Pineo, Karst Riggers, and Clark Posey showed us several sites in Eastern Washington. Terry Butler guided us on a tour of gravel extraction sites in King County. We would also like to thank Dave Norman, WDNR, and Ken Bates, WDFW for allowing us to search their literature, air photo, and report collections.

Useful personal communications and/or unpublished data were provided by George Kaminsky and Cinde Donaghue, WDOE; Steve Manlo and Sam Kolb, WDFW; Ken Cook and Dave Ward, Pierce County; Tim Randle, USBR; and Ted Poston, Pacific Northwest National Laboratory.

References

Agnelli, A., P. Billi, P. Canuti, and M. Rinaldi. 1998. Dinamica morfologica recente dell'alvedo del fiume Arno. Consiglio Nazionale delle Ricerche, Pubblicazione CNR-GNDCI No. 1739, Pacini Editore, Pisa.

Alderdice, D.W., W.P Wickett, and J.R. Brett. 1958. Some effects of exposure to low dissolved oxygen levels on Pacific salmon eggs. *Journal of the Fisheries Research Board of Canada* 15:229-250.

Allayaud, W. K. 1985. Innovations in non-structural solutions to preventing coastal damage. In J. McGrath, ed., *California's Battered Coast, Proceedings from a Conference on Coastal Erosion.* California Coastal Commission. pp. 260-290.

Allen, K.R. 1969. Limitations on production in salmonid populations in streams. In: T.G. Northcote, ed., *Symposium of salmon and trout in streams*.

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

Bairagi, N.K., K. Rorande, and V.K. Pareek. 1993. Behaviour of concrete with different proportions of natural and recycled aggregates. *Resources, Conservation, and Recycling* 9:109-126. (as cited in Poulin and Martin 1998)

Baltz, D.M., and P.B. Moyle. 1993. Invasion resistance to introduced species by a native assemblage of California stream fishes. *Ecological Applications* 3:246-255.

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

Baseline Environmental Consulting. 1992. Reclamation plan for the Kaiser Sand and Gravel Company Piombo Pit. Draft environmental impact report submitted to Sonoma County Planning Department, Santa Rosa, California.

Basher, L.R., Hicks, D.M., McSaveney, M.J., and Whitehouse, I.E. 1988. The Lower Waimakariri River floodplain: a geomorphic perspective. A report for North Canterbury Catchment Board, Department of Scientific and Industrial Research, Division of Land and Soil Sciences, Christchurch.

Batalla, R.J., and M. Sala. 1997. Estimacions hidrològiques i de moviment de sediment a la riuada del 7 d'agost de 1996 a la conca del Barranco de Arás (Pirineu aragonès). *Acta Geológica Hispánica* 30 (4): 51-59.

Batalla, R.J., C. De Jong, P. Ergenzinger, and M. Sala. 1999. Field observations on hyperconcentrated flows in mountain torrents. *Earth Surface Processes and Landforms* 24(3): 71-75.

Bates, K. 1987. Fisheries perspectives on gravel removal from river channels. p.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.

Bates, K. 1992. Floodplain gravel mining: potential fishery impacts, suggested mitigation. State Department of Fisheries, Habitat Management Division. December 26, 1992.

Bayley, P.B., and C.F. Baker. 2000. Floodplain restoration in off-channel habitats used for gravel mining in the Willamette River Basin: fish population observations in Endicott and Truax Ponds. Report to Willamette River Gravel Removal Restoration Fund Program.

Bissell & Karn. 1992. Project description, Coast Rock Products, Inc., Master plan for mining and reclamation along the Sisquoc and Santa Maria Rivers in Santa Barbara and San Luis Obispo Counties. Bissell & Karn, San Ramon, California.

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

Bjornn, T.C. 1969. Embryo survival and emergence studies. Job Completion Report. Job No. 5. Project F-49-R-7. Idaho Fish and Game Department.

Bjornn, T.L. and D.W. Reiser. 1991. Habitat requirements of salmonids in streams. In *Influences of Forest and Rangeland Management on Salmonid Fishes and their Habitats*. American Fisheries Society Special Publication. 19:83-138.

Bravard, J.P. 1994. L'incision des lits fluviaux: du phénomène morphodynamique naturel et réversible aux impacts irréversibles. *Revue de Géographie de Lyon* 69(1):5-10.

Briggs, J.C. 1953. The behavior and reproduction of salmonid fishes in a small coastal stream. *California Department of Fish and Game Fish Bulletin* 94, 62pp.

Brookes, A. 1988. *Channelized Rivers*. John Wiley & Sons, Chichester, UK.

Brown, A.V., M.M. Lyttle and K.B. Brown. 1992. Impacts of Gravel Mining on Ozark Stream Ecosystems. Fayetteville, AR, Arkansas Cooperative Fish and Wildlife Research Unit: 1-118.

Brown, A.V., M.M. Lyttle, and K.B. Brown. 1998. Impacts of gravel mining on gravel bed streams. *Transactions of the American Fisheries Society* 127: 979-994.

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. Rept. 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.

Buer, K., R. Scott, D. Parfitt, G. Serr, J. Haney, and L. Thompson. 1981. Salmon spawning enhancement studies on northern California rivers. p. 149-154 in *Proceedings: Propagation, Enhancement, and Rehabilitation of Anadromous Salmonid Populations and Habitat in the Pacific Northwest Symposium.* T.J. Hassler (ed), October 1981, California Cooperative Fishery Research Unit, Arcata, California.

Bull, W.B. and K.M. Scott. 1974. Impact of mining gravel from urban stream beds in the Southwestern United States. *Geology* 2: 171-174.

Burke, T.E., M.D. Cohen, and C.F. Scholer. 1992. Joint highway research project, synthesis study: use of concrete recycled from pavement and building rubble. School of Engineering, Purdue University. Lafayette, Indiana.

Burner, C.J. 1951. Characteristics of spawning nests of Columbia River salmon. *US Fish and Wildlife Service Bulletin* 61:97-110.

Canning, D.J. 1991. Cumulative Impacts Analysis. Unpublished report, 18 p.

Carillo, F.V., Davis, J.F., and Burnett J.L. 1990. California: Annual Report. US Department of Interior, Bureau of Mines. Washington, DC.

Carling, P.A. and N.A. Reader. 1982. Structure, composition and bulk properties of upland stream gravels. *Earth Surface Processes and Landforms* 7:349-365.

Carling, P.A., and C.P. McCahon. 1987. Natural siltation of brown trout (Salmo trutta) spawning gravels during low-flow conditions. In: Regulated streams: advances in ecology. J. F. Craig and J. B. Kemper, eds. Plenum Press, New York. 229-244.

Cederholm, C.J. and K.V. Koski. 1977. Effects of Stream Channelization on the Salmonid Habitat and Populations of Lower Big Beef Creek, Kitsap County, Washington 1969-73. Seattle, WA, Washington Cooperative Fisheries Research Unit, College of Fisheries, University of Washington: 1-31.

Cederholm, C.J. and W.J. Scarlett. 1991. The beaded channel: a low-cost technique for enhancing winter habitat of coho salmon. *American Fisheries Society Symposium* 10: 104-108.

Cederholm, C.J., and E.O. Salo. 1979. The effects of logging road landslide siltation on the salmon and trout spawning gravels of Stequaleho Creek and the Clearwater River Basin, Jefferson County, Washington, 1972-1978. Fisheries Research Institute, University of Washington, Seattle, Report No. FRI-UW-7915.

Chambers, J.S., G.H. Allen, and R.T. Pressey. 1955. Research relating to study of spawning grounds in natural areas. Annual rept. to U.S. Army Corps of Engineers, Contract no. DA.35026-Eng-20572. Avail. From Washington State Dept. Fisheries, Olympia, WA.

Chambers, J.S., R.T. Pressey, J.R. Donaldson, and W.R. McKinley. 1954. Research relating to study of spawning grounds in natural areas. Annual rept. to U.S. Army Corps of Engineers, Contract no. DA.35026-Eng-20572. Avail. From Washington State Dept. Fisheries, Olympia, WA.

Chapman, D.W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. *Transactions of the American Fisheries Society* 117(1):1-21.

Chapman, D.W. and E. Knudsen. 1980. Channelization and livestock impacts on salmonid habitat and biomass in Western Washington. *Transactions of the American Fisheries Society* 109: 357-363.

Chapman, D.W., and K.P. McLeod. 1987. Development of criteria for sediment in the northern Rockies ecoregion. Don Chapman Consultants, Boise, Idaho. Report to Battelle Columbus Laboratory under Work Assignment 2-73, EPA Contract No. 68-01-6986, 257pp.

Chevalier, B.C., C. Carson, and W.J. Miller. 1984. Report of engineering and biological literature pertaining to the aquatic environment: with special emphasis on dissolved oxygen and sediment effects on salmonid habitat. Colorado State University, ARS Project No.5602-20813-008A, available from Department of Agriculture and Chemical Engineering, Colorado State University, Fort Collins, Colorado.

Coble, D.W. 1961. Influence of water exchange and dissolved oxygen in redds on survival of steelhead trout embryos. *Transactions of the American Fisheries Society* 90:469-474.

Cohen, M. 1996. Structures and sills in river channels. p.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. 1991. River geomorphology and gravel mining in the Pilchuck River, Snohomish County, Washington . Report prepared for the Pilchuck River Coalition.

Collins, B. 1993. Sediment transport and deposition in the Lower Big Quilcene River and evaluation of planned gravel removal for flood control. Report to Dungeness-Quilcene Water Resources Pilot Planning Program, Brian Collins and Associates, Seattle.

Collins, B. 1995. Riverine gravel mining in Washington state, overview of effects on salmonid habitat, and a summary of government regulations. Unpublished report to the US EPA, Seattle.

Collins, B. 1997a. Application of geomorphology to planning and assessment of riverine gravel removal in Washington. Geology and Geomorphology of Stream Channels Conference. University of Washington, Seattle, WA. IX-1-46, January 14-15.

Collins, B. 1997b. Effects of land use on the Stillaguamish River, Washington, ~1870 to ~1990: Implications for salmonid habitat and water quality and their restoration. Report to Tulalip Tribes Natural Resources Dept., Marysville.

Collins, B., and Dunne, T. 1986. Gravel transport and gravel harvesting in the Humptulips, Wynoochee, and Satsop rivers, Grays Harbor County, Washington.

Collins, B., and Dunne, T. 1989. Gravel transport, gravel harvesting, and channel-bed degradation in rivers draining the Southern Olympic Mountains, Washington, USA. *Environmental Geology and Water Science* 13:213-224.

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

Connell, J.H. 1978. Diversity in tropical rain forests and coral reefs. *Science* 199:1302-1310.

Cooper, A.C. 1965. The effect of transported stream sediments on the survival of sockeye and pink salmon eggs and alevins. *International Pacific Salmon Committee Bulletin* No. 18, New Westminster, British Columbia.

Cordone, A.J. and D.W. Kelley. 1961. The influence of inorganic sediment on the aquatic life of streams. *California Fish and Game* 47: 189-228.

Cordone, A.J. and S. Pennoyer. 1960. Notes on silt pollution in the Truckee River drainage, Nevada and Placer Counties. California Department of Fish and Game Inland Fish. Adm. Rep. No. 60-14, 25 pp.

Correia, R.M., A.F. Andrade, and F.S. Soares. 2001. Relatório final sobre às causas do sinistro occorrido na Ponte de Entre-os-Rios em 4 de Março de 2001. Lisbon, April 2001.

Council on Environmental Quality. 1997. Considering Cumulative Effects Under the National Environmental Policy Act, Council on Environmental Quality**.** 64pp.

Creuze des Chatelliers, M. and Reygrobellet, J.L. 1990. Interactions between geomorphological processes, benthic and hyporheic communities: first results on a by-passed canal of the French upper Rhone River. *Regulated Rivers: Research and Management* 5: 139-158.

CVRSGA (Central Valley Rock, Sand & Gravel Association). 1995. Wetlands reclamation in California's Central Valley. Brochure prepared by CVRSGA, Los Banos, California.

David Brown & Associates, Inc. 2000a. Thermal transport study of the Selah Lakes gravel mine, 1999 Annual Report. Prepared for Central Pre-Mix Concrete Company, January 10, 2000.

David Brown & Associates, Inc. 2000b. Comprehensive Plan Amendment Application and SEPA Checklist, East Valley Gravel Mine, Yakima, Washington. Prepared for Central Pre-Mix Concrete Company, May 30, 2000.

Davis, J.A., J.F. Bird, and B.L. Finlayson 1997. Avon River gravel extraction study, final report. Parkville, Dept. of Civil and Environmental Engineering, The University of Melbourne: 52.

Davis, J.C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species. *J. Fish. Res. Bd. Canada* 32:2295-2332.

DeBano, L.F., Schmidt, L.J. 1989. Improving southwestern riparian areas through watershed management. USDA Forest Service.

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.

Dunne, T., W.E. Dietrich, N.F. Humphrey, and D.W. Tubbs. 1981. Geologic and geomorphic implications for gravel supply. Pp 75 - 100 in Proceedings of the Conference on Salmon-Spawning Gravel: A Renewable Resource in the Pacific Northwest? Washington Water Resource Center, Pullman.

Eitemiller, D. 1999. Progress report for the Yakima Reaches Project, August 12, 1999.

Erskine W.D. 1988 Environmental impacts of sand and gravel extraction on river systems. In *The Brisbane River*, 295-303.

Erskine, W. D., P. M. Geary, and D.N. Outhet. 1985. Potential impacts of sand and gravel extraction on the Hunter River, New South Wales. *Australian Geographical Studies* 23: 71-86.

Erskine, W.D. 1996. Environmental impacts of tidal dredging on the Brisbane River, Queensland. First National Conference on Stream Management in Australia, Merrijig, Australia.

Erskine, W.D., W.K. Tennant, and J.W. Tilleard. 1996. Sustainable sand and gravel extraction: The development of a management plan for the Goulburn River, Victoria. In: Proceedings of the First National Conference on Stream Management in Australia, Merrijig, 19-23 February, 1996.

Everest, F.L. 1987. Salmonids of western forested watersheds in *Streamside Management:*

Everts, C.H. 1985. Effects of small protective devices on beaches. P. 127-138 in J. McGrath, ed. *California's Battered Coast, Proceedings from a Conference on Coastal Erosion*. California Coastal Commission..

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.

Florsheim, J., P. Goodwin, and L. Marcus. 1998. Geomorphic effects of gravel extraction in the Russian River, California. Pp 87-99 in Aggregate Resources: a global perspective, P. Bobrowsky, ed., Balkema, Rotterdam.

Forestry and Fishery Interactions, E. O. Salo and T. W. Cundy (eds). College of Forest Resources, University of Washington, Seattle. pp. 3-8.

Forshage, A., and Carter, N.E. 1973. Effect of gravel dredging on the Brazos River. *Proceedings of the 27th Annual Conference, Southeastern Association Game and Fish Commission,* 24:695 708.

Freeze, R.A., and J.A. Cherry. 1979. *Groundwater*. Prentice Hall, Inc., Englewood Cliffs NJ.

Gaillot, S. and H. Piégay. 1999. Impact of gravel-mining on stream channel and coastal sediment supply, example of the Calvi Bay in Corsica (France). *Journal of Coastal Research* 15(3): 774788.

Galay, V.J. 1983. Causes of river bed degradation. *Water Resources Research* 19:1057-1090.

Galay, V.J. 1998. Interference with braided rivers. In: *Gravel-Bed Rivers in the Environment* (Proceedings of the Fourth International Workshop on Gravel Bed Rivers), P. Klingeman et al. (eds.). Water Resources Publications, Highlands Ranch, Colorado.

Gasowski, Z. 1994. L'enfoncement du lit de la Loire. *Revue de Géographie de Lyon* 69(1):41-45.

Gautier, E. 1994. Interférence des facteurs anthropiques et naturels dans le processus d'incision sure une rivière alpine - l'exemple du Buech (Alpes du Sud). *Revue de Géographie de Lyon* 69(1):57-62.

Geist, D.R. 2000. Hyporheic discharge of river water into fall chinook salmon (*Oncorhynchus tshawytscha*) spawning areas in the Hanford Reach, Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 57(8):1647-1656.

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

Greco, S.E. 1999. Monitoring riparian landscape change and modeling habitat dynamics of the yellow-billed cuckoo on the Sacramento River, California. Ph.D. dissertation. University of California, Davis.

Greeley, J.R. 1932. The spawning habits of brook, brown, and rainbow trout and the problem of egg predators. *Transactions of the American Fisheries Society* 62: 239-248.

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

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

Groot, C., and L. Margolis. 1991. *Pacific salmon life histories*. University of British Columbia Press, Vancouver. 564 pp.

Hamilton, J.D. 1961. The effect of sand-pit washings on a stream fauna. *Verh. Internat. Verein. Limnol* 14: 435-439.

Hardy, C.J. 1963. An examination of eleven stranded redds of brown trout (*Salmo trutta*)excavated in the Selwyn River during July and August, 1960. *New Zealand J. Sci*. 6:107-119.

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkamper. 1986.Ecology of Coarse Woody Debris in Temperate Ecosystems. Advances in Ecological Research. A. MacFadyen and E. D. Ford. New York, NY, Harcourt Brace Jovanovich. 15: 133-302.

Harshbarger, T.J., and P.E. Porter. 1982. Embryo survival and fry emergence from two methods of planting brown trout eggs. *North American Journal of Fisheries Management* 2:84-89.

Harvey, M.D. and S.A. Schumm. 1987. Response of Dry Creek, California, to land use change, gravel mining and dam closure. In *Erosion and Sedimentation in the Pacific Rim, Proceedings of the Corvallis Symposium, August 1987*, International Association of Hydrological Sciences Publication 165:451-460.

Harvey, M.D., and T.W. Smith. 1998. Gravel Mining Impacts on San Benito River, California. In: Proceedings of 1998 International Water Resources Engineering Conference, Hydraulics Division, ASCE, Memphis, TN, August 1998.

Hawke, S.P. 1978. Stranded redds of quinnat salmon in the Mathias River, South Island, New Zealand. *N.Z. J. Mar. Freshwater Res*. 12:167-171.

Healey, M.C. 1991. Life history of chinook salmon. p. 311-394 in Groot, C., and Margolis, L., *Pacific salmon life histories*. University of British Columbia Press, Vancouver. 564 pp.

Hecht, B. 1994. South of the spotted owl: restoration strategies for episodic channels and riparian corridors in central California. In: Kent, D.M., and J.T. Zentner, eds., Western Wetlands, selected proceedings of the 1993 conference of the Society of Wetland Scientists., p.104-117.

Hillmann, F.R. 1991. Recycling rubble: does it have to be a "no win" business proposition? *Canadian Aggregate* 5(1): 24-25. (As cited in Poulin and Martin 1998).

Hobbs, D.F. 1937. Natural reproduction of quinnat salmon, brown and rainbow trout in certain New Zealand waters. *New Zealand Marine Department Fisheries Bulletin* 6, 104pp.

Hubbs, C.L., Greeley, J.R., Tarzwell, C.M. 1932. Methods for the improvement of Michigan trout streams. *Bulletin of the Institute for Fisheries Research* 1: 1-54.

Hupp, C.R., and W.R. Osterkamp. 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14: 277-295.

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. p. 10-15, in J. McGrath (ed.) California's Battered Coast, Proceedings from a Conference on Coastal Erosion, San Diego, February 1985. 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, CA.

Jefferson County Conservation District. Undated. Big Quilcene River Cross Sections. Unpublished data report.

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

Jenks, S.P. 1989. Stillaguamish River coho salmon (*Oncorhynchus kisutch*) off-channel habitat enhancement project. Washington State Department of Fisheries, 148-155 pp.

Johnson, W.C. 1992. Dams and riparian forests: case study from the upper Missouri River, *Rivers*, 3, 229-242 pp.

Kanehl, P. and J. Lyons. 1992. Impacts of In-stream sand and gravel mining on stream habitat and fish communities, including a survey on the Big Rib River, Marathon County, Wisconsin. Wisconsin Department of Natural Resources Research Report 155, August 1992.

Keith, S.B. 1969. Sand and gravel. P.424-441 in Mineral and Water Resources of Arizona. *Arizona Bureau of Mines Bulletin* 180.

Kellerhalls, R. 1982. Effect of river regulation on channel stability. p. 685-715 in *Gravel-bed rivers*. R.D. Hey, J.C. Bathurst, and C.R. Thorne, eds. John Wiley and Sons, New York.

Kelso, D.D. 1996. Channel migration, gravel mines, and public policy in the East Fork Lewis River, Clark County, Washington. University of California, Berkeley. 14 pp.

Klein, R., D. Jager, B. Trush, A. Lehre. 1999. County of Humboldt Extraction Review Team (CHERT) 1998 post-extraction report. Prepared for the Humboldt County Board of supervisors, February 1,1999.

Klingeman, P.C. 1979. Short-term considerations on river gravel supply. *Salmon-Spawning Gravel Conference Proceedings* p. 123-139.

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. 1997. Hungry water: effects of dams and gravel mining on river channels. *Environmental Management* 21(4): 533-551.

Kondolf, G.M. 1998. Environmental effects of aggregate extraction from river channels and floodplains. p. 113-129 in *Aggregate resources: a global perspective*, P. Bobrowsky, ed. Balkema, Rotterdam.

Kondolf, G.M. 2000. Assessing salmonid spawning gravel quality. *Transactions of the American Fisheries Society* 129:262-281.

Kondolf, G.M., A. Falzone, and K.S. Schneider. 2001. Reconnaissance-level assessment of channel change and spawning habitat on the Stanislaus River below Goodwin Dam. Report to the U.S. Fish and Wildlife Service, Sacramento, California.

Kondolf, G.M., and D.D. Kelso. 1996. Effects of aggregate mining in river floodplains: Some observations relevant to the policy on floodplain mining in Clark County, Washington. Comments submitted to the Clark County Planning Commission, April 1996.

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

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 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 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., 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.

Koski, K.V. 1966. The survival of coho salmon (*Oncorhynchus kisutch*) from egg deposition to emergence in three Oregon coastal streams. MS thesis, Oregon State University, Corvallis. 84pp.

Kroft, D.J. 1972. Sand and gravel deposits in western King County, Washington. MS thesis, University of Washington, Seattle, 62pp.

Lacy, M.K. 1996. Reclaiming surface mined land to waterfowl habitat. *California Geology* 49(March/April): 36-43.

Lagasse, P.F. and D.B. Simons. 1979. Impact of dredging on river system morphology. P. 434-457 in Proceedings of Specialty Conference on Utilization of Water and Energy Resources. American Society of Civil Engineers, New York.

Lagasse, P.F., D.B. Simons, and B.R. Winkley. 1980. Impact of gravel mining on river system stability. *Journal of the Waterway Port Coastal and Ocean Division ASCE* 106: 389-404.

Landon, N. and H. Piégay. 1994. L'incision de deux affluents subméditerranéens du Rhône: la Drôme et l'Ardèche. *Revue de Géographie de Lyon* 69(1):63-72.

Landon, N., H. Piegay, and J.P. Bravard. 1998. The Drome river incision (France): from assessment to management. *Landscape and Urban Planning* 43: 119-131.

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. 15 p. (in Hebrew)

Larson, D.W. 1996. Brown's Woods: an early gravel pit forest restoration project, Ontario, Canada. *Restoration Ecology* 4(1): 11-18.

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.

Leighton, M.M. 1919. The road building sands and gravels of Washington. *Washington Geological Survey Bulletin* 22.

Leopold, L.B. and M.G. Wolman. 1957. River channel patterns -- braided, meandering and straight. *U.S. Geological Survey Professional Paper* 282B:39-95.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. *Fluvial Processes in Geomorphology.* W.H. Freeman Co. San Francisco, California. 522 pp.

Li, R.M. and D.B. Simons. 1979. Mathematical modeling of erosion and sedimentation associated with instream gravel mining. Specialty Conference on Utilization of Water and Energy Resources. 420-429, August 8-11, 1979 (see Lagasse …1979).

Lingley, W.S., and C.J. Manson. 1992. Directory of Washington mining operations, 1992. *Washington Division of Geology and Earth Resources Information Circular* 87, 76 p.

Lisle, T. and S. Hilton. 1991. Fine sediment in pools: an index of how sediment is affecting a stream channel. *FHR Currents Fish Habitat Relationship Technical Bulletin* 6: 1-7.

MacDonald, A. 1988. Predicting channel recovery from sand and gravel extraction in the Naugatuck River and adjacent floodplain. p.702-707 in *Hydraulic Engineering*, Proceedings of the National Conference, American Society of Civil Engineers Hydraulics Division, Colorado Springs, Colorado.

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.

Marston, R. A., J. Girel, G. Pautou, H. Piegay, J.P. Bravard, C. Arneson 1995. Channel metamorphosis, floodplain disturbance, and vegetation development: Ain river, France. *Geomorphology* 13: 121-131.

Mas-Pla, J., J. Montaner, and J. Sola. 1999. Groundwater resources and quality variations caused by gravel mining in coastal streams. *Journal of Hydrology* 216: 197-213.

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, California.

McBain and 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.

McMichael, G., A.L. Fritts, T.N. Pearson. 1999. Lower Yakima River Predatory Fish Monitoring: Progress Report 1988. In: *Management implications of co-occurring native and introduced fishes*, Proceedings of the Oregon Department of Fish and Wildlife Workshop, Portland, October 7-28, 1999, Oregon.

McNeil, W.J., and W.H. Ahnell. 1964. Success of pink salmon spawning relative to size of spawning bed materials. *Special Sci. Report Fish*. 469, US Fish and Wildlife Service, Washington DC.

Milhous, R.T. 1982. Effect of sediment transport and flow regulation on the ecology of gravel bed rivers, in *Gravel Bed Rivers*, edited by R.D. Hey, J.C. Bathurst, and C.R. Thorne p.819-841 John Wiley and Sons, Chichester, U.K.

Miller, D.E., P.B. Skidmore, and D.J. White. 2001. Channel design. White paper submitted to WDFW, WDOE, and WDOT.

Mossa, J. and W.J. Autin. 1998. Geologic and geographic aspects of sand and gravel production in Louisiana. p. 439-463 in *Aggregate resources: a global perspective*, P. Bobrowsky, ed. Balkema, Rotterdam.

Moyle, P.B. 1976. Some effects of channelization on the fishes and invertebrates of Rush Creek, Modoc County, California. *Calif. Fish and Game* 62: 179-186.

Needham, P.R. 1961. Observations on the natural spawning of eastern brook trout. *California Fish and Game*, 47. 27-40.

Netsch, N., L.A. Rundquist, and L.L. Moulton. 1981. Effects of floodplain gravel mining in Alaska on physical factors important to salmon spawning. p. in 154-167 in Proceedings of the Conference on Salmon Spawning Gravel Conference: A Renewable Resource in the Pacific Northwest? Washington Water Resources Center, Pullman.

Norman, D.K. 1998. Reclamation of Flood-Plain Sand and Gravel Pits as Off-channel Salmon Habitat. *Washington Geology* 26:21-28.

Norman, D.K., C.F. Cederholm, and W.S. Lingley. 1998. Flood plains, salmon habitat, and sand and gravel mining. *Washington Geology* 26:3-20.

Northwest Hydraulics Consultants. 1987. Dungeness River Study: Final report. Submitted to Clallam County Dept of Public Works, Port Angeles.

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.

NRC. 1992. Restoration of aquatic ecosystems: science, technology, and public policy. National Research Council Committee on Restoration of Aquatic Ecosystems, National Academy Press, Washington D.C.

Ottaway, E.M., P.A. Carling, A. Clarke, and N.A. Reader. 1981. Observations on the structure of brown trout (*Salmo trutta* Linneas) redds. *Journal of Fisheries Biology* 19:593-607.

Page, K.J. and R.G. Heerdegen. 1985. Channel Change on the Lower Manawatu River. *New Zealand Geographer* 41: 35-38.

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., Thomas, G.L., Marino, D.A., and Weigand, D.C. 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.

Peiry, J.L. 1987. Short communication: Channel degradation in the Middle Arve River, France. *Regulated Rivers: Research and Management* I:183-188.

Peiry, J.L., P.G. Salvador, and F. Nouguier. 1994. L'incision des rivières dans les Alpes du nord: état de la question. *Revue de Géographie de Lyon* 69(1):47-56.

Peterson, N.P. 1982. Immigration of juvenile coho salmon (*Oncorhynchus kisutch*) into riverine ponds. *Canadian Journal of Fisheries and Aquatic Sciences* 39: 1308-1310.

Petit, F., D. Poinsart, and J.P. Bravard. 1996. Channel incision, gravel mining and bedload transport in the Rhône river upstream of Lyon, France ("Canal de Mirabel"). *Catena* 26:209-226.

Phillips, R.W., R.L. Lantz, E.W. Claire, and J.R. Moring. 1975. Some effects of gravel mixtures on emergence of coho salmon and steelhead trout fry. *Transactions of the American Fisheries Society* 104:461-466.

Pickett, S.T.A., and P.S. White. 1985. Patch dynamics: a synthesis. pp 371-0384 in S.T.A. Pickett and P.S. White, *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press.

Poff, N.L., D.J. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, J.C. Stromberg. 1997. The natural flow regime. *Bioscience* 47: 769-784.

Poulin, R. and W.S. Martin. 1998. Economics of recycled aggregates p.215-229 in *Aggregate resources: a global perspective*, P. Bobrowsky, ed. Balkema, Rotterdam.

Poulin, R., R.C. Pakalnis, and K. Sinding. 1994. Aggregate resources: Production and environmental constraints. *Environmental Geology* 23: 221-227.

Power, M.E., W.E. Dietrich, and J.C. Finlay. 1996. Dams and downstream aquatic biodiversity: potential food web consequences of hydrologic and geomorphic change. *Environmental Management* 20:887-895.

Prych, E.A. 1988. Flood-carrying capacities and changes in channels of the Lower Puyallup, and Carbon Rivers in Western Washington. U.S. Geological Survey Water - Resources Investigations Rept. 87-4129.

Reily, P.W. and C.W. Johnson 1982. The effects of altered hydrological regime on tree growth along the Missouri river in North Dakota. *Canadian Journal of Botany* 60: 2410-2423.

Reingold, M. 1965. A steelhead spawning study. *Idaho Wildlife Review* 17:8-10.

Resh, V.H., A.V. Brown, A.P. Covich, M.E. Gurtz, H.W. Li, G.W. Minshall, S.R. Reice, A.L. Sheldon, J.B. Wallace, and R.C. Wissmar. 1988. The role of disturbance in stream ecology, *Journal of the North American Benthological Society* 7: 433-455.

Richards, C., P.J. Cernera, Ramey, M.P., and Reiser, D.W. 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, UK. 358 pp.

Rinaldi, M. and A. Simon. 1998. Bed-level adjustments in the Arno River, central Italy. *Geomorphology* 22:57-71.

Rivier, B. and J. Seguier. 1985. Physical and biological effects of gravel extraction in river beds. p. 131-146 in J.S. Alabaster, ed. *Habitat modification and freshwater fisheries*. Food and Agric. Organ. U.N., Rome. 278 pp.

Rowan, J.S. and J.J. Kitetu. 1998. Assessing the environmental impacts of sand harvesting from Kenyan rivers. p. 331-354 in *Aggregate resources: a global perspective.* P. T. Bobrowsky, ed., Balkema Rotterdam.

Sacramento County. 1987. Supplemental environmental impact report for Teichert (Aspen IV-A) Land Company use permit. Sacramento County Planning and Community Development Department, Sacramento. Control No. 87-UP-0232.

Sandecki, M. 1989. Aggregate mining in river systems. *California Geology.* 42:88-94.

Sandecki, M. and C.C. Avila. 1997. Channel adjustments from instream mining: San Luis Rey River, San Diego County, California. *Geological Society of America Reviews in Engineering Geology* XI: 39-48.

Sandercock, F.K. 1991. Life history of coho salmon (*Oncorhynchus kisutch*). p. 395-446 in C. Groot and L. Margolis, eds. *Pacific salmon life histories* University of British Columbia Press, Vancouver. 564 p.

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

Schultz, P. 1990. Disused gravel mines provide skiing and boating for Denmark. *Landscape Architecture* 80:30-32.

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.

Scott, M.L., E.D. Eggleston, G.T. Auble, J.M. Freidman, L.S. Ischinger. 1995. Effects of Gravel Mining on Natural Cottonwood Stands. 6th Annual Colorado Riparian Conference.

Scott, M.L., G.C. Lines, and G.T. Auble. 1999. Channel incision and patterns of cottonwood stress and mortality along the Mojave River, California. *Journal of Arid Environments* 44: 399-414.

Scott, M.L., J.M. Friedman. G.T. Auble. 1996. Fluvial process and the establishment of bottomland trees. *Geomorphology* 14:327-339.

Scott, M.L., P.B. Shafroth, and G.T. Auble. 1999. Responses of riparian cottonwoods to alluvial water table declines. *Environmental Management* 23: 347-358.

Sear, D.A., and Archer, D.R. 1998. The effects of gravel extraction on the stability of gravel-bed rivers: a case study from the Wooler Water, Northumberland, UK. p. 415-432 in Gravel-Bed Rivers in the Environment (Proceedings of the Fourth International Workshop on Gravel Bed Rivers), P. Klingeman et al. eds., Water Resources Publications, Highlands Ranch, Colorado.

Shields, F.D., A. Simon, and L.J. Steffen. 2000. Reservoir effects on downstream channel migration. *Environmental Conservation* 27:54-66.

Shumway, D.L., C.E. Warren, and P. Duodoroff. 1964. Influence of oxygen concentration and water movement on the growth of steelhead trout and coho salmon embryos. *Transactions of the American Fisheries Society* 93:342-356.

Silver, J., C.E. Warren, and P. Duodoroff. 1965. Dissolved oxygen requirements of developing steelhead and chinook salmon embryos at different water velocities. *Transactions of the American Fisheries Society* 92:327-343.

Smith, M.R., and L. Collis. 1993. Aggregates *Engineering Geology Special Publication* No.9 (second edition). Geological Society, London. pp. 95-97.

SOGREAH. 1991. Etude de diagnostic de la nappe de la basse vallee de la Drome. Direction Departmentale de l'equipment de la Drome, report and maps (in French).

Soil & Water. 1985. Attacks on the Otaki - Gravel or grants? Anonymous article in *Soil & Water*, magazine of the National Water and Soil Conservation Authority, Wellington, New Zealand 21:2-6.

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.

Sparks, R.E., P.B. Bayley, et al. 1990. Disturbance and Recovery of Large Floodplain Rivers. *Environmental Management* 14: 699-709.

Stanford, J.A. 1998. Floodplain ecology of the Yakima River, Washington: Historical Condition, Current Status and Prospects for Restoration of Critical Habitat for Anadromous Salmonids, a proposal to the Bureau of Reclamation, November 6, 1998.

Starnes, L.B. 1983. Effects of surface mining on aquatic resources in North America. *Fisheries* 8:2-4.

Starnes, L.B. and D.C. Gasper. 1995. Effects of Surface Mining on Aquatic Resources in North America. *Fisheries* 20: 20-24.

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

Stone, K.E., and B.S. Kaufman. 1985. Sand rights, a legal system to protect the shores of the beach. p. 280-297, *in* J. McGrath (ed.) *California's Battered Coast*, Proceedings from a Conference on Coastal Erosion, San Diego, February 1985.

Stuart, T.A. 1953. Water currents through permeable gravels and their significance to spawning salmonids, etc. *Nature* 172: 407-408.

Sutek Services, Ltd. and Kekerhals Engineering Services, Ltd. 1989. Assessing gravel supply and removal in fisheries stream. Report to Dept. of Fisheries and Oceans and British Columbia Ministry of Environment.

Tagart, J.V. 1984. Coho salmon survival from egg deposition to emergence. p.173-181 in *Proceedings of the Olympic Wild Fish Conference* J.M. Walton and D.B. Houston, eds. Port Angeles, Washington, March 1983.

Tagliavini, S. 1978. Le modificazioni geomorphologiche ed idrogeologiche conseguenti all'attivita estrattiva nella conoide del torrente Enza. In: *Proceedings of the Conference on Attivita Estrattiva dei Materiali Inerti da Costruzioni.Effetti sugli Ambienti e Risorse Alternative* (in Italian).

Taig, M. 1996. Use of sediment accumulated in flood reservoirs. p.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)

Tautz, A.F. and C. Groot. 1975. Spawning behavior of chum salmon (*Oncorhynchus keta*) and rainbow trout (*Salmo gairdneri*). *Journal of the Fisheries Research Board of Canada* 22:633-642.

Tepordei, V.V. 1992. Construction sand and gravel: annual report. US Department of Interior, Bureau of Mines. Washington, DC.

Thomas, R.B. 1985. Estimating total suspended sediment yield with probability sampling. *Water Resources Research* 21: 1381-1388.

Thorne, C.R. 1997. Channel types and morphological classification. p. 175-222 in *Applied Fluvial Geomorphology for River Engineering and Management*, C.R. Thorne, R.D. Hey, and M.D. Newson (eds.). John Wiley & Sons, Chichester.

Todd, A.H. 1989. The decline and recovery of Blackwood Canyon, Lake Tahoe, California in *Proceedings International Erosion Control Association Conference*, Vancouver British Columbia.

USACE (US Army Corps of Engineers) 2000. Interim Lower Snake, Clearwater, and Mid-Columbia Rivers dredging Environmental Assessment. U.S. Army Corps of Engineers, Walla Walla, Washington.

Van den Berge, E.P., and M.R. Gross. 1984. Female size and nest depth in coho salmon *(Oncorhynchus kisutch) Canadian journal of fisheries and aquatic sciences.* 41:204-206.

Vaux, W.G. 1968. The flow and interchange of water in a streambed. *US Fish and Wildlife Service Fishery Bulletin* 66:479-489.

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.

Vining, L.J., and B.M. Freeman. 1985. An evaluation of the incubation life-phase of chum salmon in the Middle Susitna River, Alaska. Alaska Dept. of Fish and Game Winter Habitat Investigations (September 1983 - May 1984) Rept. no. 5, Vol. 1.

Vronskiy, B.B. 1972. Reproductive biology of the Kamchatka River chinook salmon (*Oncorhynchus tschawytscha* (Walbaum)). *Journal of Ichthyology* 12:259-273.

Ward, J.V. and J.A. Stanford. 1995. Ecological connectivity in alluvial rivers and its disruption by flow regulation. *Regulated Rivers: Research and Management* 11: 105-119.

Warner, R.F. 1994. Instability in channels and floodplains in southeast Australia: natural processes and human activity impacts. *Revue de Géographie de Lyon* 69(1):17-24.

WDNR (Washington Department of Natural Resources). 1989. Gravel removal from rivers for reducing flood risk. Washington Departments of Natural Resources and Ecology, Olympia, Washington.

Weigand, D.C. 1991. Effects of gravel scalping on juvenile salmonid habitat. University of Washington, Seattle. 149 pp.

Wilcock, P.R., G.M. Kondolf, W.V.G. Matthews, and A.F. Barta. 1996. Specification of sediment maintenance flows for a large gravel-bed river. *Water Resources Research* 32:29112921.

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

Williams, P.B., L. Fishbain, K.G. Coulton, and B. Collins. 1995. A restoration feasibility study for the Big Quilcene River. Report to Washington Wildlife Heritage Foundation by Philip Williams and Associates, San Francisco, California.

Wo, Y.G. and T.R. Healy. 1994. Degradation of the Lower Waikato River: An Analysis of the Gauging Data. *Journal of Hydrology* 32: 29-43.

Woodward-Clyde Consultants. 1980. Gravel removal studies in arctic and subarctic floodplains in Alaska. US Fish and Wildlife Service Biol. Serv. Progress Rep., FWS/OBS-80/08.

Wootton, J.T., M.S Parker, and M.E. Power. 1996. Effects of disturbance on river food webs. *Science* 273:1558-1561.

Young, M.K., W.A. Hubert, and T.A. Wesche. 1990. Fines in redds of large salmonids. *Transactions of the American Fisheries Society* 119:156-162.

Zeibell, C.D. and S.K. Knox. 1957. Turbidity and siltation studies, Wynoochee River. Washington Pollution Control Commission. Olympia, Washington, 7 p.