Effects of Suction Dredging on Streams: a Review and an Evaluation Strategy

By Bret C. Harvey and Thomas E. Lisle

ABSTRACT

Suction dredging for gold in river channels is a small-scale mining practice whereby streambed material is sucked up a pipe, passed over a sluice box to sort out the gold, and discarded as tailings over another area of bed. Natural resource managers should be concerned about suction dredging because it is common in streams in western North America that contain populations of sensitive aquatic species. It also is subject to both state and federal regulations, and has provided the basis for litigation. The scientific literature contains few peer-reviewed studies of the effects of dredging, but knowledge of dredging practices, and the biology and physics of streams suggests a variety of mechanisms linking dredging to aquatic resources. Effects of dredging commonly appear to be minor and local, but natural resource professionals should expect effects to vary widely among stream systems and reaches within systems. Fishery managers should be especially concerned when dredging coincides with the incubation of embryos in stream gravels or precedes spawning runs soon followed by high flows. We recommend that managers carefully analyze each watershed so regulations can be tailored to particular issues and effects. Such analyses are part of a strategy to (1) evaluate interactions between suction dredging and other activities and resources; (2) use this information to regulate dredging and other activities; (3) monitor implementation of regulations and on- and off-site effects of dredging; and (4) adapt management strategies and regulations according to new information. Given the current level of uncertainty about the effects of dredging, where threatened or endangered aquatic species inhabit dredged areas, fisheries managers would be prudent to suspect that dredging is harmful to aquatic resources.

S uction dredging for gold is a small-scale mining practice whereby streambed material is excavated from a wetted portion of a river channel and discarded elsewhere. Suction dredges use high-pressure water pumps driven by gasoline-powered motors to create suction in a flexible intake pipe [commonly 75-300 cm (3 in-12 in) in diameter]. The intake pipe sucks streambed material and water and passes them over a sluice box that is usually mounted on a floating barge. Dense particles (including gold) are trapped in the sluice box. The remainder of the material is discharged into the stream and can form piles of tailings or spoils. Large boulders, stumps, and rootwads may be moved before excavating a site, and rocks too large to enter the intake pipe are piled nearby. Dredging can vary in area from a few small excavations to the entire wetted area in a reach and can exceed several meters in depth. Material is commonly dredged from pools and cast over downstream riffle crests.

Suction dredging is common during the summer in many river systems in western North America. It can affect aquatic and riparian organisms (Griffith and Andrews 1981; Thomas 1985; Harvey 1986), channel stability (T. E. Lisle and B. C. Harvey, personal observation), and the use of river ecosystems for other human activities.

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Suction dredging is regulated by both state and federal agencies, based in part on the U.S. General Mining Law of 1872, Organic Administration Act of 1897, and Clean Water Act of 1972. Suction dredging is an important issue to fisheries professionals because many dredged streams contain threatened or endangered species, and the adequacy of agency management of suction dredging has been legally challenged. Surprisingly, the effects of suction dredging on river ecosystems have not been studied extensively. A literature search yielded only five journal articles that specifically address the effects of suction dredging (Griffith and Andrews 1981; Thomas 1985; Harvey 1986; Hall 1988; Somer and Hassler 1992). However, some impacts of dredging can be predicted from general knowledge of physical and biological processes in streams.

Our goals in this paper are to summarize potential effects of suction dredging on stream biota and physical channel characteristics and to propose a basin-scale strategy for evaluating the effects of suction dredging. We also identify several research areas critical to improving management of suction dredging in streams.

On-site effects of dredging

Entrainment of organisms by suction dredges

State regulations generally limit dredging to summer months, but dredging can still overlap with fish spawning and incubation of embryos. In some streams salmonids do not emerge from the substrate until summer, and many

nonsalmonids have protracted spawning periods extending into summer (Moyle 1976).

Griffith and Andrews (1981) observed a range of mortality rates for aquatic organisms entrained into a suction dredge. Mortality among benthic invertebrates in four Idaho streams was generally low (<1% of more than 3,600 individuals) but was highest among an emerging mayfly species. In contrast, entrainment increased mortality of the early life history stages of trout. Mortality was 100% among un-eyed eggs of cutthroat trout (*Oncorhynchus clarki*) from natural redds but decreased to 29%-62% among eyed eggs. Similar tests at a commercial hatchery with eyed eggs of rainbow trout (*O. mykiss*) revealed little difference in mortality after 10 d between a control group (18% mortality) and a group that passed through a dredge along with gravel (19% mortality). Sac fry of hatchery rainbow trout suffered >80%o mortality following entrainment, compared to 9% mortality for a control group. Entrainment in a dredge also would likely kill larvae of other fishes. Sculpins (Cottidae), suckers (Catostomidae), and minnows (Cyprinidae) all produce small larvae (commonly 5 mm-7 mm at hatching) easily damaged by mechanical disturbance. Eggs of nonsalmonid fishes, which often adhere to rocks in the substrate, also are unlikely to survive entrainment. Fish eggs, larvae, and fry removed from the streambed by entrainment that survived passage through a dredge would probably suffer high mortality from subsequent predation and unfavorable physico-chemical conditions.
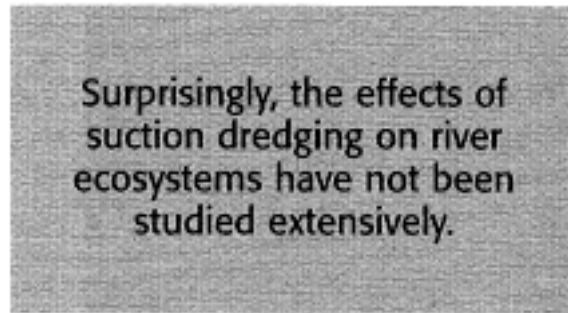
Most juvenile and adult fishes are likely to avoid or survive passage through a suction dredge. All 36 juvenile and adult rainbow and brook trout (*Salvelinus fontinalis*) entrained intentionally by Griffith and Andrews (1981) survived. Adult sculpin also can survive entrainment (B. Harvey, personal observation).

Effects of excavation on habitat

Direct disturbance of streambeds, including dredging, tends to destabilize natural processes that mold stream channels. Channel topography, bed particle size, and hydraulic forces in undisturbed natural channels mutually adjust so variations in stream flow and sediment supply usually create only modest changes from year to year (Dietrich and Smith 1984; Nelson and Smith 1989). These adjustments allow a channel to transport its load of sediment. Excavation by dredging directly causes significant local changes in channel topography and substrate conditions, particularly in small streams. The resulting destabilization may increase local scour or fill in parts of the streambed that were not directly disturbed. Because hydraulic forces and sediment transport rates vary widely among and within channels from year to year, the persistence of dredging-related alterations also can vary widely. For example, dredged channels would be less likely to be remolded annually if they were downstream of impoundments or diversions that decrease peak flows and trap bedload.

Dredging that excavates streambanks may have long-lasting effects because streambanks are commonly slow to rebuild naturally (Wolman and Gerson 1978). Erosion of streambanks is likely to be greater where (1) streambanks and riparian vegetation are directly disturbed by suction dredging and related activities; (2) streambanks are composed of erodible materials such as alluvium; (3) dredging artificially deepens the channel along streambanks; and (4) the roughness of streambanks and the adjacent bed is reduced. Bank roughness in the form of large rocks, roots, and bank projections tends to reduce hydraulic forces on streambanks (Thome and Furbish 1995).

Dredging near riffle crests (the transition between pools and riffles) also can pose special problems for channel stability. If dredging causes riffle crests to erode, spawning sites may be destabilized, and upstream pools may become shallower. Disturbance of riffle crests also can destabilize the reach immediately downstream. Riffle crests are commonly flat, so any imposed topography would tend to deflect the flow to one side of the channel downstream, promoting bank erosion, and scour and fill of the bed (Figure 2). Dredge tailings placed in different locations from year to year would exacerbate these impacts.

In some locations excavations may temporarily improve fish habitat. Pools can be temporarily formed or deepened by dredging. Deep scour may intersect subsurface flow and create pockets of cool water during summer, which can provide important habitat for fish (Nielsen et al. 1994). At low flows, increased water depth can provide a refuge from predation by birds and mammals (Harvey and Stewart 1991). Harvey (1986) observed that all eight fish occupying a riffle during late summer in Butte Creek, California, moved into a dredged excavation nearby. However, dredged excavations are usually short-lived because they tend to be filled with sediment during high flows.

Piling of cobbles

Miners commonly pile rocks too large to pass through their dredges. These piles can persist during high flows and, as imposed topographic high points, may destabilize channels during high flows, as previously described. Piles of cobbles probably have only minor, local effects on the abundance of aquatic organisms. Taxa that strongly select large, unembedded substrate [e.g., speckled dace (*Rhinichthyes osculus*)] might become more abundant where cobbles are piled.

Deposition o f tailings

Sediment mobility

Gravel and coarse sand cast downstream during dredging tend to remain as loose tailings because there is insufficient power to transport them downstream. Fine sediment (clay, silt, and fine sand) will be carried further

> Surprisingly, the effects of suction dredging on river ecosystems have not been studied extensively.

downstream in suspension, but minor proportions of this material are usually present in gravel streambeds (Lisle 1989). Moreover, a single dredging operation cannot mobilize significant volumes of fine sediment compared with the volume mobilized during high seasonal discharge, when erosional sources deliver fine sediment from the watershed and widespread areas of the streambed are entrained.

Benthic invertebrates

Exposure of new substrate and deposition of tailings locally reduce the abundance of benthic invertebrates. Both

A miner works upstream of these dredges in Butte Creek, California, at a depth of greater than 2 meters.

This is the same site in spring of the following year. The log at water's edge in the upper, center-right of this photograph is visible in the upper center of the photo above.

Thomas (1985) and Harvey (1986) measured significant reductions in some benthic invertebrate taxa within 10 m of dredges that disturbed the substrate. Harvey (1986) found that large-bodied insect taxa that avoid sand (e.g., hydropsychid caddisflies and perlid stoneflies) were most affected. These results are consistent with reduced benthic invertebrate abundance and species richness after complete embedding of larger substrate by fine sediment (e.g., Brusven and Prather 1974; Bjornn et al. 1977; McClelland and Brusven 1980). Somer and Hassler (1992) measured colonization of artificial substrates upstream and downstream of active dredges and found differences in assemblage composition but not in overall abundance. However, their artificial substrates were initially silt-free, while the surrounding substrate was not.

In general, benthic invertebrates (Mackay 1992), hyporheic invertebrates (Boulton et al. 1991), and periphyton (e.g., Stevenson 1991; Stevenson and Peterson 1991) all rapidly recolonize small patches of new or disturbed substrate in streams. Abundance and general taxonomic composition of benthic invertebrates can be restored on dredge tailings four to six weeks after dredging (Griffith and Andrews 1981; Thomas 1985; Harvey 1986). In the three studies cited above, dredging disturbed only a minor proportion of available habitat for benthic invertebrates. Recolonization on tailings would probably be slower if dredging were more extensive because potential colonizers would be less abundant and more remote. However, recovery of benthic invertebrate communities after even large-scale disturbances (e.g., Minshall et al. 1983) suggests that both the total number of individuals and species diversity could recover even in areas of widespread dredging.

However, not all benthic inver-tebrates can be expected to rapidly recolonize disturbed areas. For example, many mollusks have low dispersal rates (Gallardo et al. 1994) and limited distributions in river systems (Green and Young 1993). Many aquatic insects also have limited geographic ranges (e.g., Erman and Nagano 1992). Populations of such species may be influenced strongly by local events such as suction dredging. Unfortunately, only about one-quarter of the freshwater mussels in the United States and Canada have stable abundances (Williams et al. 1993), and little is known about mussels in states where suction dredging is common (California, Idaho, Oregon, Washington). The challenge of evaluating the effects of dredging on aquatic invertebrates is often exacerbated by a lack of taxonomic information.
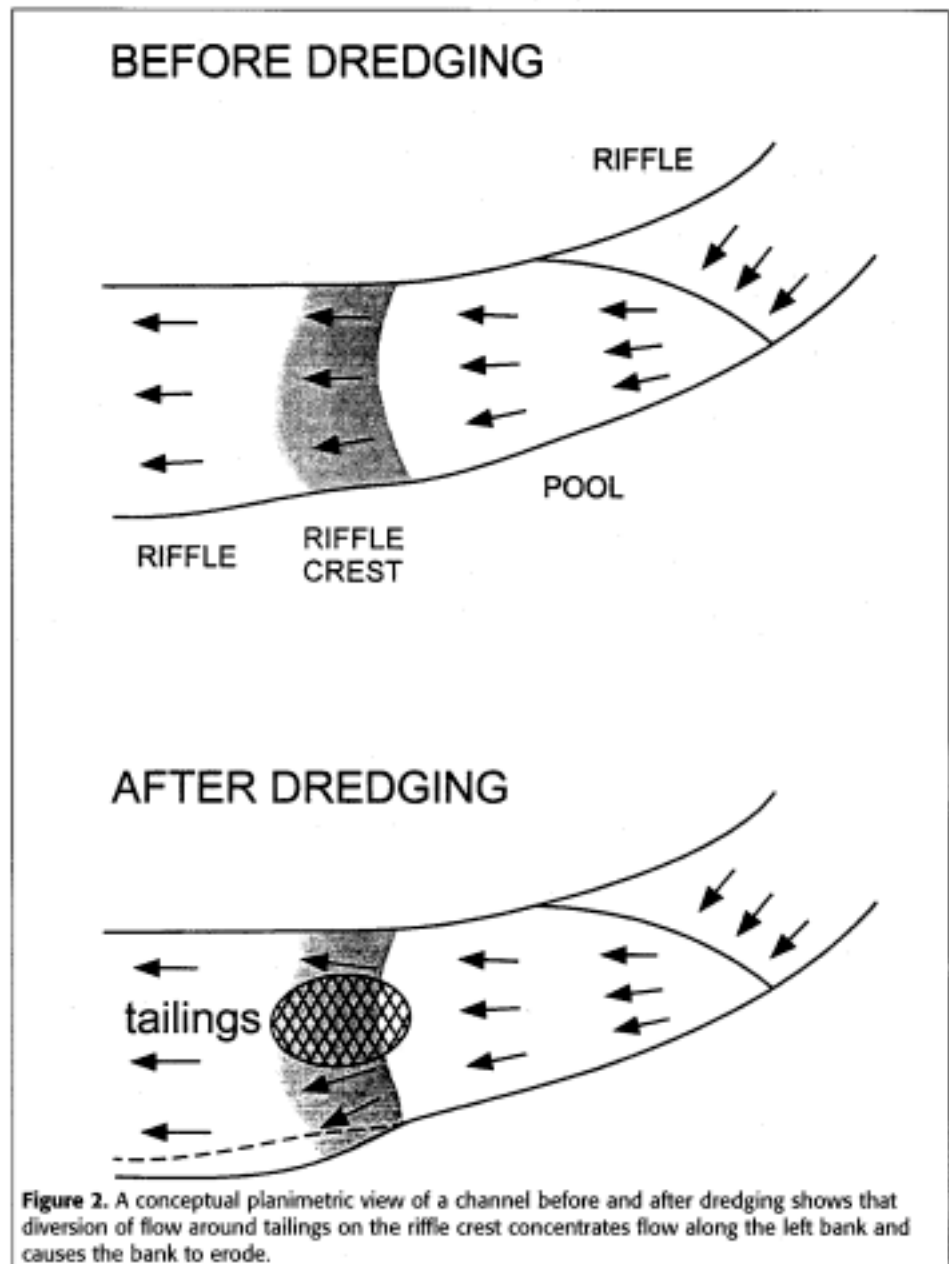
Stability of spawning gravels

Deposition of dredge tailings also may affect fish reproduction by inducing fish to spawn on unstable material (T. E. Lisle and B. C. Harvey, personal observation). Substrate stability is critical to spawning success of fall-spawning species because the weeks or months of embryo development in the gravel commonly coincide with the season of high flows that mobilize streambeds (Holtby and Healey 1986; Lisle and Lewis 1992). The coarseness of natural armor layers indicates the power of flows to move bed material (Parker and Klingeman 1982; Dietrich et al. 1989), so dredge tailings of fine gravel and sand that are cast over much coarser bed material (cobbles and boulders) have a high potential for scouring. State regulations in Idaho and Washington require dredge operators to backfill holes and level tailings, thereby increasing their stability.

Dredge tailings may be attractive to salmonids as sites for redd (nest) construction because tailings are often located near riffle crests where fish frequently spawn, and they provide relatively loose, appropriately sized substrate. However, dredge tailings may reduce embryo survival because they tend to be less stable than natural spawning gravels. Embryos in tailings may suffer high mortality if high flows scour the tailings, thereby destroying the redds.

The risk depends in part on the timing of spawning and high flows. Tailings are likely to be remolded or removed by high flows, providing greater stability afterwards. For example, fall spawners [chinook salmon

Figure 2. A conceptual planimetric view of a channel before and after dredging shows that diversion of flow around tailings on the riffle crest concentrates flow along the left bank and causes the bank to erode.

(*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*)] in northwestern California spawned on fresh tailings that were later completely scoured by seasonal high flows (T. Lisle and B. Harvey, personal observation). In contrast, unstable tailings are likely to be gone or remolded before reproduction by later-spawning species such as steelhead (*O. mykiss*).

Little information exists on the selection of tailings by spawning fish. Hassler et al. (1986) noted that chinook salmon, coho salmon, and steelhead all spawned on dredge tailings in Canyon Creek in northwestern California. Three of eight spring chinook salmon redds, one of one coho redd, and one of eleven steelhead redds were located on dredge tailings. Selection of dredge tailings for spawning cannot be evaluated without knowing the overall availability of spawning gravels. However, spawning gravel was not in short supply in Canyon Creek, suggesting that tailings were not avoided by spawning fish (Hassler et al. 1986).

Tailings may significantly increase the availability of spawning sites for salmonids in channels lacking spawning gravel such as those that are armored with cobbles and boulders too large to be moved by spawning fish (Kondolf et al. 1991). However if such tailings are unstable, the population-level consequences of dredging could be negative. Considering the decline of populations Chinook salmon and coho salmon in western North America (Nehlsen et al. 1991), we think information on the relative stability of tailings and their use for spawning by these species is needed.

The relationship between suction dredging and spawning may require special consideration in regulated rivers. Impoundments commonly reduce sediment supply and peak flows downstream. Dredging may loosen and locally flush fine sediment from static streambeds, with little danger of redds being disturbed during egg incubation. However, we suspect that long-term improvement of spawning habitat by

dredging downstream of dams is rare. Annual dredge mining (and renewal of spawning gravels) may not be sustainable because gold-bearing pockets would tend to be mined out without replenishment by new sediments. At the same time, dredge holes and tailings may be more persistent below impoundments, perhaps leaving these areas less suitable for recreation.

Fish habitat

Tailings also may influence juvenile and adult fishes, particularly if habitat depth and volume are altered substantially. Habitat depth is positively related to the abundance and/or size of salmonids (Everest and Chapman 1972) and other stream fishes (Harvey and Stewart 1991). The number of rainbow trout in a small pool in Butte Creek, California, declined by 50% after dredging upstream filled 25% of the pool volume (Harvey 1986). Clearly, small channels are more vulnerable to dredging impacts than large channels. For example, the entire width of small channels may be spanned by dredge tailings, creating shallow riffles that inhibit the longitudinal movement of aquatic organisms.

Some stream fishes can be affected by changes in substrate composition alone. Juveniles and adults of some benthic fish species (e.g., sculpin and dace) often occupy microhabitats beneath unembedded cobbles and boulders (Baltz et al. 1982; Harvey 1986). Harvey (1986) observed significantly reduced densities of juvenile and adult riffle sculpin (*Cottus gulosus*) downstream of a dredge on the North Fork of the American River, California, and attributed the decline in part to burial of cobbles by dredge tailings.

Movement of large roughness elements

Dredge operators may remove coarse woody debris (CWD) and large boulders from stream channels or reduce the stability of these elements by removing surrounding material. (Removing these elements from the stream is prohibited in some states.) Many pools are formed by scour around large roughness elements (Keller and Swanson 1979; Lisle 1986a; Montgomery et al. 1995). Large pieces and conglomerations of CWD are especially important because they cause scour of larger pools and can be more stable than smaller pieces (Bilby 1984). Furthermore, large roughness elements such as CWD can govern the location of scour and deposition at the scale of pools and riffles (Lisle 1986b; Montgomery et al. 1995).

Many studies provide evidence that CWD and other large elements affect various ecological processes and conditions in streams, including the microbial uptake and transfer of organic matter (Tank and Winterbourn 1996), the species composition and productivity of benthic invertebrates (Benke et al. 1984), and the density of fish (e.g., Fausch and Northcote 1992; Crispin et al. 1993). While fish may not always be associated with large substrate elements, these features may be limiting during critical events such as concealment by salmonids in winter (Heggenes et al. 1993; Smith and Griffith 1994) or reproduction by sculpins (Mason and Machidori 1976; Moyle 1976).

Suction dredging is likely to affect large roughness elements only locally, but because CWD has been depleted in many western streams by other human activities (Bilby and

Ward 1991; Ralph et al. 1994), resource managers may still need to consider this issue.

Behavioral responses to dredging

Behavioral responses of stream biota to noises and vibrations generated by dredging have not been quantified. This issue appears insignificant for many taxa. Sculpin close to active dredges appear to behave normally (B. Harvey, personal observation), and juvenile salmonids have been observed feeding on entrained organisms at dredge outfalls (Thomas 1985; Hassler et al. 1986). However, Roelofs (1983) expressed concern that dredging could frighten adult summer-run steelhead, based on their response to divers. Spring-run chinook and summer-run steelhead adults held within 50 m of active dredges in Canyon Creek, California, (Hassler et al. 1986) but dredging may have inhibited upstream movement by the fish. Even minor disturbances during the summer may harm adult anadromous salmonids because their energy supply is limited, and the streams they occupy can be near lethal temperatures (Nielsen et al. 1994).

Off-site effects of fine sediment mobilized by dredging

Suspended sediment

High concentrations of suspended sediment can alter survival, growth, and behavior of stream biota (Newcombe and MacDonald 1991). Impacts of suspended sediment can increase with (1) longer exposure time (Newcombe and MacDonald 1991), (2) smaller sediment particle size (Servizi and Martens 1987), (3) extremes in temperature (Servizi and Martens 1991), and (4) higher organic content of the sediment (McLeay et al. 1987). Extremely high levels of suspended sediment (e.g., >9,000 mg/L) can be lethal to aquatic biota, and lethal thresholds may be lower under natural conditions (Bozek and Young 1994) than in the laboratory (Redding et al. 1987).

Even slightly elevated suspended sediment may reduce reactive distance of salmonids to drifting prey (Barrett et al. 1992) and prey capture success (Berg and Northcote 1985). Growth rates of steelhead and coho salmon in laboratory channels were higher and their emigration rates lower in clear water than in turbid water (22-286 NTU) after 11-21 d (Sigler et al. 1984). In contrast, feeding by sculpin in laboratory channels was not detectably affected by suspended sediment levels of 1,250 mg/L (Brusven and Rose 1981).

Any reduction in feeding efficiency of fish may be offset by reduced risk of predation at moderate levels of suspended sediment. Juvenile chinook salmon spend more time foraging in water of moderate turbidity (20-25 NTU) than in clearer water (Gregory 1993). Similarly, brook trout are more active and spend less time near cover in moderately turbid water than in clear water (Gradall and Swenson 1982). Juvenile estuarine fishes in laboratory channels actively seek moderate turbidity (Cyrus and Blaber 1987). Coho salmon do not avoid turbidities as high as 70 NTU but move into turbid water when frightened (Bisson and Bilby 1982).

One of the most obvious off-site effects of dredging is increased suspended sediment because background concentrations where and when dredging occurs are usually low. However, lethal concentrations of suspended sediment are

probably rarely produced by suction dredging. Field measurements of changes in turbidity and suspended sediment below suction dredges indicate minor, localized effects. For example, turbidity was 0.5 NTU upstream, 20.5 NTU 4 m downstream, and 3.4 NTU 49 m downstream of an active dredge on Canyon Creek (Hassler et al. 1986). Suspended sediment concentrations at the same three locations were 0, 244 mg/L, and 11.5 mg/L, respectively. On Butte Creek and the North Fork of the American River where ambient turbidities were <1 NTU, maximum turbidity 5 m downstream of active dredges reached 50 NTU but averaged only 5 NTU (Harvey 1986). In Gold Creek, Montana, suspended sediment was 340 mg/L at the dredge outflow and 1.8 mg/L 31 m downstream of an active dredge (Thomas 1985). Extrapolating results from studies exposing biota to chronic suspended sediments may overestimate the impacts of dredging because dredgers commonly operate for <5 h/d.

Unfortunately, the results cited here do not eliminate the possibility that dredging can affect stream biota via increased suspended sediments. Mobilization of suspended sediment by dredging and resulting effects on biota are site-specific. Production of suspended sediment is no doubt linked to the size and frequency of dredging operations, but such cumulative effects have not been evaluated. Dredging in streambeds in which sand is the dominant interstitial fine sediment is unlikely to yield high suspended sediment concentrations, but excavation of streambanks anywhere is likely to substantially increase suspended sediment because banks commonly contain abundant finer sediments.

Deposition of fine bedload

Neither the extent of off-site deposition and transport of dredging-generated fine sediment (clay, silt, and sand) nor the responses of aquatic biota have been investigated in a variety of streams. These issues deserve consideration because fine sediment can alter a variety of stream processes and conditions, including primary production (e.g., Power 1990), density of aquatic insects (e.g., Hogg and Norris 1991), and fish reproduction (e.g., Phillips et al. 1975; Fudge and Bodaly 1984).

While silt and clay entrained by dredging may remain suspended and travel long distances before being deposited, sand and gravel are usually deposited immediately downstream. At low flows pools tend to accumulate sediment transported as bedload (Keller 1971). Thus, pools can be filled by sediments mobilized by upstream dredging (Thomas 1985; Harvey 1986). While deposition of bedload would be most severe close to dredging sites, disruption of the continuity of bedload transport can have unpredictable consequences downstream, including both erosion and deposition (Womack and Schumm 1977). However, unless significant bank erosion occurs, increased sediment transport is limited by the fact that the sediment load delivered to the channel remains the same, and overall effects downstream are probably minor. Furthermore, lower channel stability by itself may not be important to some aquatic ecosystems**.**

Deposition of fine sediment downstream of active dredges is unlikely to substantially decrease water depth, but it may increase the embeddedness of cobble and boulder substrates used by many organisms. Complete embedding of substrates (particularly by silt and clay) generally will severely harm assemblages of benthic invertebrate (Hogg and Norris 1991). Slight increases are unlikely to significantly reduce the density of benthic invertebrates. In fact, partially embedded substrate may support a more-dense, diverse invertebrate fauna than unembedded substrate (Bjornn et al. 1977). Neither Thomas (1985) nor Harvey (1986) detected differences in the abundances of invertebrates 10 m or more downstream of dredged areas versus abundances at upstream control sites. However, these studies had low probabilities of detecting differences for several reasons: (1) High spatial variability occurred in the abundances of benthic invertebrates (even under natural conditions); (2) slow-water habitats where silt and clay may have been deposited were not sampled in either study; (3) sand dominated the fine sediments of the streams sampled in both studies; and (4) Harvey (1986) could not sample in the deepest parts of the channel where dredging-generated bedload was concentrated because of limitations of the sampling device.

Downstream transport and deposition of fine sediment also can reduce availability of microhabitats used by benthic fish. Density of sculpin was lower downstream of dredge tailings on the North Fork of the American River, in part because of increased deposition of sand (Harvey 1986). Similar to benthic fishes, amphibian larvae and adults might be harmed by reduced habitat beneath cobbles and boulders. For example, Parker (1991) measured a strong positive response by Pacific giant salamader larvae (*Dicamptodon tenebrosus*) to the addition of cobbles to a stream dominated by smaller substrate.

Deposition and transport of fine sediment by dredging is less likely to affect fish that occupy the water column during summer. Repeated visual censuses and observations of tagged fish revealed no short-term response to dredging by rainbow trout in pools in Butte Creek where substrate embeddedness and the percentage of fine sediment were increased, but habitat depth and volume were not changed substantially (Harvey 1986). Similarly, Bjornn et al. (1977) observed only minor differences in salmonid density in artificial channels with unembedded versus half-embedded gravel, cobble, and boulder substrates. However, if extensive dredging reduced invertebrate production, then salmonids could be affected. For example, Crouse et al. (1981) found a negative relationship between coho salmon production and the amount of fine sediment in the substrate of laboratory streams that lacked allochthonous inputs of invertebrates.

Bedload transport *per se* also may need to be considered when examining off-site effects of dredging on benthic invertebrates and fish. Culp et al. (1986) observed short-term reductions in invertebrate abundance from increased transport of fine bedload in a natural riffle where the composition of the substrate was not altered greatly. In addition, dredging-caused increase in transport

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of fine sediment may have harmed sculpin at the North Fork of the American River (Harvey 1986): relatively few sculpin occupied microhabitats beneath cobbles and boulders that remained unembedded downstream of the dredge.

Reproduction by spring-spawning animals will not be affected by the deposition of fine bedload where high winter discharge entrains these sediments. However, temporal overlap of dredging and reproduction by species of concern may produce significant off-site effects of dredging. For example, fine sediment deposition over more than 4 km below 4 suction dredges in Piru Creek, California, apparently reduced survival of eggs and larvae of the endangered Arroyo toad (*Bufo microscaphuus californicus*) throughout a significant proportion of the known range of the species (Sweet 1992).

Effects of multiple dredges

Off-site effects of individual dredges may be minor, but downstream impacts may be of concern where dredges are closely spaced, and other human activities and natural conditions increase the potential for cumulative effects. A moderate density of dredges in Butte Creek generated minor increases in sedimentation, and cumulative effects on benthic invertebrates or rainbow trout were not detected (Harvey 1986). However, no research has been dedicated to measuring the cumulative physical or biological effects of many closely spaced dredges. Cumulative effects of dredging and other human activities deserve attention, particularly where reaches are dredged year after year. Experiments will be difficult to conduct because of the length of stream reach that would comprise a reasonable unit of observation and variability among reaches (Carpenter et al. 1995). An experimental approach to management (McAllister and Peterman 1992) that included measurements on streams varying strongly in dredging intensity would help answer questions about cumulative effects.

Activities associated with dredging

Examination of dredging impacts also should include activities commonly associated with dredging such as camping and fishing. Dredge operators often camp in riparian zones that are critical to birds, amphibians, and aquatic insects. Miners' campsites are seldom maintained by resource agencies, so waste disposal and control of site damage is usually left to the miners. Sites are usually occupied for long periods. Some mining claims are used by a series of dredge operators in one season, leading to intense activity in one area. Also, fishing by miners may intensify pressure on local populations.

Analyzing suction dredging in a watershed context

Effects of suction dredging must be analyzed in the context of individual stream systems. The potential for a variety of dredging effects is great, and the distribution of physical and biological attributes and human activities in each stream basin is unique. In many systems, dredging effects may be minor when considered in isolation, yet they may contribute to significant cumulative effects on important resources. A methodology to accurately identify general thresholds of dredging activity leading to unacceptable cumulative effects is not available. A useful strategy is to adapt a watershed-scale approach to identify and evaluate important conflicts between dredging and aquatic

organisms. A general strategy for analyzing dredging impacts parallels those outlined in existing management guidelines that include ecosystem analyses at the watershed scale (e.g., FEMAT 1993; Washington Forest Practices Board 1993; Regional Ecosystem Office 1995). Ideally, analysis of suction dredging would be part of a comprehensive examination that addresses all important issues for a particular watershed. The following steps might be included in either a specific analysis of dredging or an overall watershed analysis:

(1) Evaluate interactions between suction dredging and other activities and resources by

A. identifying and prioritizing issues (other activities and resources) that could be affected by dredging and associated activities.

B. identifying and evaluating probable on- and off-site effects of dredging on conditions and processes important to these issues. How strong are these effects? How and when do they occur? How far do they extend? How long do they last? How do they interact with other human disturbances?

C. analyzing how patterns of dredging and disturbances overlay patterns of potentially affected activities and resources.

(2) Use this information to develop guidelines for dredging and other activities. Even an exhaustive analysis is unlikely to reveal an indisputable, definite threshold of acceptable dredging activity. Instead, limits and regulations for each stream system will need to be decided openly in a scientifically informed, political process.

(3) Monitor implementation of regulations, on-site effects of dredging on key physical and biological parameters, and off-site effects of dredging on downstream conditions and processes. Take an experimental approach to monitoring that includes contrasts among different management strategies (McAllister and Peterman 1992).

(4) Alter management strategies and regulations in response to monitoring results, new issues, and changing physical and biological conditions in the watershed.

Examples of the analysis strategy

A. Fish populations

In many western streams where dredging occurs, managers will identify the population viability of one or more fishes as an issue of concern (Step 1.A.). In this case, the following questions might arise (Step 1.B.):

(1) Are fish in early life stages (e.g., eggs, larvae, alevins) present during dredging?

(2) Does dredging increase suspended sediment to levels that could affect fish, and are the likely effects negative or positive?

(3) Do environmental conditions (e.g., high water temperature or fine sediment with high organic content) raise the risk to fish populations of increased suspended sediment?

(4) What is the probability that fish will spawn before dredge spoils are reworked by high flows?

(5) If eggs are deposited in dredge tailings, what is the probability that flows capable of transporting bed material will occur during the incubation period?

(6) What is the stability of dredge spoils relative to natural spawning areas?

(7) To what extent does dredging significantly change the volume of channel geomorphic units or the loss of large substrate elements?

And in analyzing patterns (Step 1.C.):

(1) Does dredging occur in stream reaches that are hotspots of spawning activity?

(2) Are natural spawning gravels in such short supply that a large percentage of spawners might use dredge tailings?

(3) What is the probability that dredging-related mortality will significantly affect fish populations? (Does the area affected comprise a significant or key proportion of a population's range?)

(4) How does the overall impact of dredging on fish populations compare to, or interact with, other possible impacts such as fishing?

Answers to these questions may suggest changes in dredging techniques (Step 2). For example, if dredging occurs where existing fall-spawning chinook salmon are limited by recruitment, then requiring that tailing piles be obliterated could reduce the threat to reproductive success from spawning on unstable tailings.

Issues and impact mechanisms identified in the analysis (Step 1) would logically focus monitoring (Step 3) of the effectiveness of new regulations (Step 2). For example, if destabilization of fall spawning gravels is a problem, managers would want to survey the proportion of redds located on tailings and measure the relative stability of redds on spawning gravels that have and have not undergone post-dredging restoration. This could be done with repeated topographic surveys or scour monitoring devices (Nawa and Frissell 1993).

B. Channel stability

Where channel stability is identified as an issue of concern, a geomorphologist might be enlisted to help answer the following questions (Step 1.B.):

(1) How much will the original bed topography, including the particle size and morphology of pools and riffle crests, be altered by dredging?

(2) Will streambanks be subjected to increased hydraulic forces?

(3) Is the channel likely to reconstruct its original form given typical peak flows?

(4) Will coarse woody debris and other large roughness elements that influence channel morphology be disturbed?

Step 1.C.:

(1) What is the extent of channel morphological effects, and how are dredging sites distributed relative to other disturbances (e.g., fires and roads) and inherently unstable reaches (e.g., those with alluvial streambanks, low gradients, or multiple channels)?

(2) What other factors such as large floods, impoundments, and large sediment inputs affect channel stability, and how does the impact of dredging interact with these factors?

Scoping the problem of channel stability in Step 1 should indicate reaches to monitor because of their inherent instability and proximity to dredging operations. On- and off-site channel changes could be monitored with repeated topographic surveys or aerial photography. At the same time, flood stages and other disturbances (e.g., grazing, landslides, and fires) also would be monitored.

Conclusions

Suction dredging and associated activities have various effects on stream ecosystems, and most are not well understood. In some situations, the effects of dredging may be local and minor, particularly when compared with the effects of other human activities. In others, dredging may harm the population viability of threatened species. Dredging should be of special concern where it is frequent, persistent, and adds to similar effects caused by other human activities. Fishery managers should be especially concerned when dredging coincides with the incubation of young fish in stream gravels or precedes spawning runs (e.g., fall-run chinook salmon) soon followed by high flows. They also should be concerned about increased fine-sediment deposition in channels that naturally contain abundant fine sediment or receive inputs from other disturbances.

We recommend that basin-scale analyses of dredging and other activities be performed so regulations can be tailored to particular issues and effects in each stream system. Quantitative, uniform guidelines and regulations that are truly applicable and scientifically supportable for a variety of basins probably will never be found. Instead, basin-specific regulations will need to be created in a political but scientifically informed process using information from a basin-scale analysis. Considering the uncertainty surrounding dredging effects, declines in many aquatic animal populations, and increasing public scrutiny of management decisions, the cost of assuming that human activities such as dredging cause no harm deserves strong consideration by decision makers (Mapstone 1995). Where threatened or endangered species exist, managers would be prudent to assume activities such as dredging are harmful unless proven otherwise (Dayton 1998).)

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