Regulated Flushing in a Gravel-Bed River for Channel Habitat Maintenance: A Trinity River Fisheries Case Study

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ABSTRACT / The operation of Trinity and Lewiston Dams on the Trinity River in northern California in the United States, combined with severe watershed erosion, has jeopardized the existence of prime salmonid fisheries. Extreme streamflow depletion and stream sedimentation below Lewiston have resulted in heavy accumulation of coarse sediment on riffle gravel and filling of streambed pools, causing the destruction of spawning, nursery, and overwintering habitat for prized chinook salmon (*Salmo gairdnerii*) and steelhead trout (*Oncorhynchus tschawytscha*). Proposals to restore and maintain the degraded habitat include controlled one-time remedial peak flows or annual maintenance peak flows designed to flush the spawning gravel and scour the banks, deltas, and pools. The criteria for effective channel restoration or maintenance by streambed flushing and scouring are examined here, as well as the mechanics involved.

The liabilities of releasing mammoth scouring–flushing flows approximating the magnitude that preceded reservoir construction make this option unviable. The resulting damage to fish habitat established under the postproject streamflow regime, as well as damage to human settlements in the floodplain, would be unacceptable, as would the opportunity costs to hydroelectric and irrigation water users. The technical feasibility of annual maintenance flushing flows depends upon associated mechanical and structural measures, particularly instream maintenance dredging of deep pools and construction of a sediment control dam on a tributary where watershed erosion is extreme. The cost effectiveness of a sediment dam with a limited useful economic life, combined with perpetual maintenance dredging, is questionable.

The once outstanding salmon and trout fisheries of the Trinity River declined after the completion of the Trinity River Division of California's Central Valley Project, which created a major new supply of irrigation water and hydroelectric power. The federal Bureau of Reclamation and the US Fish and Wildlife Service, together with many California agencies, have intensively researched the options for restoring these fisheries. This rich documentation, once it is screened and integrated with research findings elsewhere, presents a comprehensive basis for a definitive case study.

The large potential resource benefits from mitigating the adverse effects of substantial streamflow depletion and severe watershed erosion also make this case ideal for assessing all aspects of managing gravel-bed streams by flushing accumulated sand and silt with controlled reservoir releases. Alternative or complementary management measures, particularly channel maintenance dredging, and sediment impoundment on tributaries affected by heavy erosion, also are examined here.

Federal and state water resource management agencies are trying to determine the need for flushing flows below many dams, both new and old. Although flushing flows are the focus of the case study, they are only one of many measures available for the comprehensive management of instream sediment.

KEY WORDS: Flushing; Scouring; Channel maintenance; Fisheries; Trinity River

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Project History

The Trinity River drainage lies in the Klamath Mountains of northwestern California in the United States, west of Redding and Shasta Lake and east of Eureka and Redwood National Park. The mainstem river is approximately 275 km (170 miles) long and drains a 7640-km^2 (2950-mi^2) watershed, originating at the 2400-m (8000-ft) elevation in northern Trinity County. It is the largest tributary to the Klamath River, joining the Klamath 65 km (40 mi) from the Pacific Ocean at a 90-m (300-ft) elevation.

Before 1960, the Trinity was typical of most unregulated streams in northern California. The 63-km (39-mi) river reach from Lewiston to the North Fork, with a gradient of 2.8 m/km (15 ft/mi), contained extensive riffles that were heavily used by salmon and steelhead trout (*Salmo gairdnerii*) for spawning. This reach supported the greatest concentration of spawning chinook salmon (*Oncorhynchus tschawytscha*). Since 1960, the mainstem Trinity has been regulated by the Central Valley Project, providing a firm yield of 1230×10^6 m^3/year (1,000,000 ac-ft/yr), primarily for irrigation and hydropower production.

In 1956, construction began on Lewiston Dam, a reregulating dam 11 km (7 mi) below Trinity Dam (Figure 1) that produces extreme fluctuations from generating hydropower; streamflows were first impounded in 1960 and diversions from Lewiston Reservoir began in 1963. Since then, about 85%–90% of the average surface runoff upstream of Lewiston Dam has been diverted by tunnels out of the Trinity River basin to the Sacramento River. These diversions have transformed the discharge characteristics of the Trinity River at Lewiston so that it now has relatively low and constant year-round and seasonal flows.

The annual peak flows that once flushed stream sediment are now absent. Preproject mean monthly flows ranged from 4.2 to 115 m^3/s (150 to 4000 cfs), with peaks of 140–1100 m^3/s (5000–39,000 cfs), whereas streamflows below Lewiston in the postproject years 1963–1978 generally ranged from 4.5 to 15 m^3/s (160 to 525 cfs). The reduced flows have less capacity to entrain and transport sediment, particularly where coarse sand is deeply embedded in gravel. Below Grass Valley Creek, the bedload carrying capacity was 150,000 m^3/yr (200,000 yd^3/yr) before the reservoir project but was reduced to about 7500 m^3/yr (10,000 yd^3/yr) following dam construction (California Resources Agency 1970).

The quantity and quality of anadromous fish habitat have been seriously reduced since construction and operation of the dams. Trinity and Lewiston Dams have blocked the access of migratory fish to 95 stream kilometers (59 stream miles) of chinook salmon habitat, 175 km (109 mi) of steelhead trout habitat, and an undetermined amount of coho salmon (*O. kisutch*) habitat. The remaining accessible river environment shows significant reduction in wetted perimeter, spawning riffles, and pools for rearing juveniles and holding adults.

In response to the need for increased attention to declining commercial and sport fisheries, the Trinity River Fish and Wildlife Task Force has been working since the early 1970s to identify and resolve the problems responsible for the losses in anadromous fish populations. As stream sedimentation is a major problem, the methods of removing accumulated sediment, mainly coarse granitic sands, and of preventing future accumulation have been carefully evaluated. One alternative studied is the use of large releases from Lewiston Dam to flush out the heavy existing deposits or to maintain a clean streambed once the heaviest deposits are removed by other means.

Although the Task Force did not formally recommend a flushing flow regime, the basis for the planned allocation of 420×10^6 m^3 (340,000 ac-ft) of releases did include 40×10^6 m^3 (32,000 ac-ft) for sediment flushing and fish migration purposes (US Fish and Wildlife Service 1983). Ultimately, the Task Force preferred to rely on structural and mechanical means for controlling instream sediment, particularly the construction of a sediment dam on Grass Valley Creek and dredging of sand from the mainstem river. It appears, however, that a maintenance flushing flow used as a *supplemental* measure would be consistent with Task Force intentions.

Impacts of Reduced Flows

The Trinity River spawning habitat below Lewiston Dam has suffered an overall reduction of 44%, but the losses in the 63-km (39-mi) reach from the dam to the North Fork are approximately 80%–90%, with the greatest damage concentrated in the 16-km (10-mi) river reach between Grass Valley and Indian Creeks (see Figure 1) (Frederiksen and others 1980). The potential fall-run chinook natural spawning population of 71,000 has diminished to about 11,250, according to estimates by Frederiksen and associates. They estimated egg-to-smolt and smolt-to-adult survival rates for unregulated and regulated flow events and combined these with spawning escapement.

The main causes of habitat reduction are identified as the loss of flushing flows associated with natural flood events and the high sediment production from extensive land disturbance on erodible sandy soils (California Resources Agency 1970, Megahan 1979, VTN Environmental Sciences 1979, US Fish and Wildlife Service 1980a and b, Frederiksen and others 1980, Strand 1981). The resultant impacts include the burial of stream riffles necessary to benthic invertebrates and spawning salmonids, the partial filling of streambed pools important to overwintering juveniles, the formation of deltas at the mouths of tributaries, the spread of riparian growth into the streambed, and a constricted stream channel.

The elimination of peak flood flows has stimulated the rapid encroachment of riparian vegetation in the

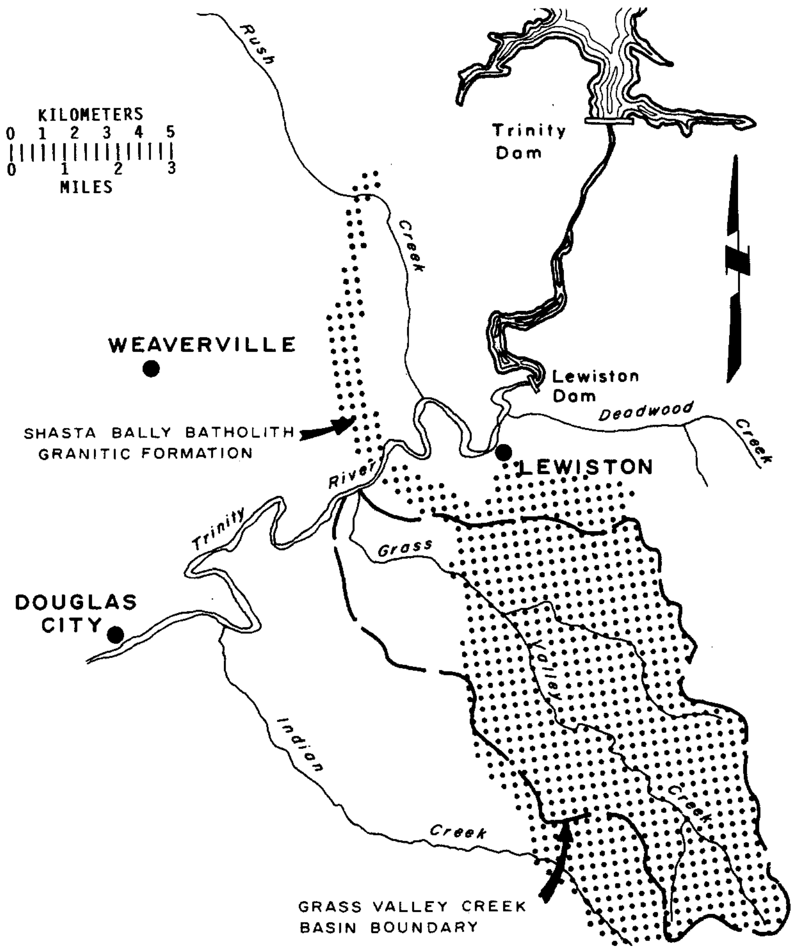

Figure 1. Trinity River drainage area associated with the heaviest impacts from streamflow depletion and stream sedimentation below Lewiston Dam (Frederiksen and others 1980).

floodplain and into the river channel. The changes in the channel resulting from decreased streamflows, especially natural flushing flows, and from the spread of vegetation were accelerated by sediment loading from the decomposed Shasta Bally batholith granitic formation that concentrates in the Grass Valley Creek watershed (Figure 1). Extensive land disturbance from forest clearcutting, logging road construction, grazing, and mining have exacerbated the natural susceptibility of these soils and steep terrain to erosion.

Tributary sediment flow into the mainstem river, especially from Grass Valley Creek, has filled streambed pools required as nursey and wintering habitat, has compacted and even buried spawning riffle gravel, and has further promoted the encroachment of vegetation leading to the constriction and channelization of the river.

Changes in the condition of the Trinity River since 1960 are closely correlated with declining populations of anadromous fish. Increased sedimentation and reduced flows have resulted in the deterioration of habitat for chinook salmon and steelhead trout in particular. Habitat losses have resulted from the combination of damage to stream riffles, runs, and pools and alterations at the banks and tributary confluences.

The new, attenuated flow regime does not allow for flood flows that would mobilize gravels and large cobbles, flush gravel-embedded sands, and uproot any sprouting vegetation in the streambed. Under the historical Trinity River flow conditions at Lewiston, flows of a magnitude sufficient to move the bed materials were equaled or exceeded from 10% to 40% of the time (Frederiksen and others 1980). Under present conditions, flows sufficient to move the gravel bed have, for the most part, been eliminated from Lewiston Dam downstream to Grass Valley Creek (Figure 2) and drastically reduced from Grass Valley Creek to the North Fork. Below the North Fork, present flows are similar to historic levels.

The elimination of abrasive flood flows and a new river regime of stable flows between October and May have resulted in the spread of riparian vegetation. The root systems of the plants have grown into the river channel, binding spawning gravels and inducing silta-

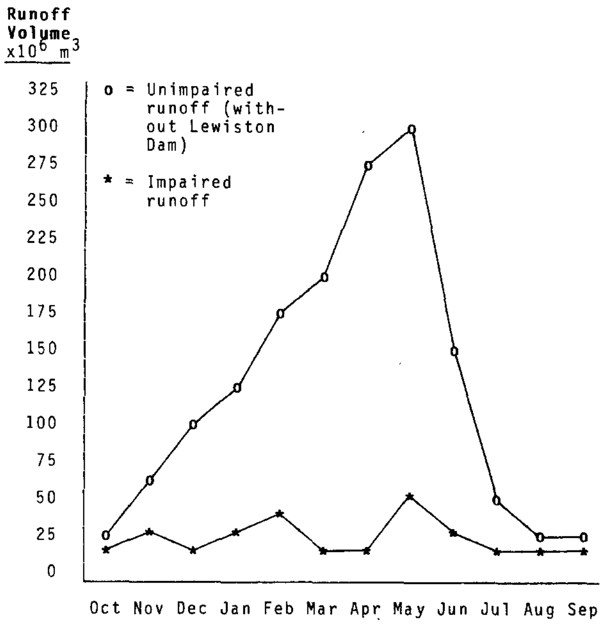

Figure 2. Mean monthly runoff and streamflow at Lewiston, based on 1922–1960 streamgage data and current Lewiston Dam operating schedule (Frederiksen and others 1980).

tion. The encroaching vegetation binds and protects the streambank material from future erosion that might occur with random (or planned) high flows, and also causes increased channelization during elevated flows.

As the river channel constricts, flows are concentrated into a narrowed channel; water velocity therefore increases, often exceeding levels suitable for fish spawning, and the channel is further incised and the banks steepen. Vegetated cut banks can make good rearing cover but continued channelization can eventually destroy the shallow-water, low-velocity cover that juvenile fish use for feeding, resting, and escaping from predators. Shallow riffles and the total wetted perimeter, both important factors in the production of fish food organisms, have been lost in this process.

Benthic invertebrates, mainly aquatic insects with a lifespan of about one year, are the major food source for anadromous fish. Frederiksen and associates (1980) observe that invertebrates cannot change their stream location when shifts occur in the water surface. Consequently, the lowest flows of the year determine the sites where these organisms are most numerous; riffle gravel submerged year-round contributes most to fish food production.

Most deep pools (3–6 m or 10–20 ft) between Grass Valley Creek and the Steel Bridge 9.3 km (5.8 mi) downstream have been filled gradually to a depth of 0.9–1.8 m (3–6 ft) and greatly reduced in area. Although this depth is still suitable as holding habitat, the area reduction has profoundly altered the pool–riffle ratio affecting the rearing of juveniles and resting of migrating adults. While verifying these conditions, Strand (1981) also estimated the large tonnages of accumulated sediment in this particular reach below Grass Valley Creek (Table 1).

The primary concerns related to sand and silt accumulation in the gravel are the effects on spawning, egg survival, fry emergence, rearing, and wintering over of juveniles in the substrate. Sand in the interstices of the gravel is not by itself a serious problem unless it occupies over 35% of the void space (Frederiksen and others 1980). But a high interstitial sand content traps silts and clays that can be harmful to eggs and sac fry (alevins), even in small quantities, by lowering intragravel permeability and the supply of dissolved oxygen to the eggs or alevins. The consequence may be lower egg survival and stunted size of the fry at emergence (Tagart 1976).

A US Environmental Protection Agency study compared the bed composition of the Trinity River and its tributaries with that of unregulated Idaho streams supporting important salmon fisheries (Platts and others 1979). The streams in Idaho lie within disturbed and undisturbed watersheds in a batholith formation similar to that in the Trinity basin. The Trinity riffle beds were found to contain three times as many fines <0.07 mm in diameter as did the unregulated streams, which indicates potentially poor survival and growth of eggs and alevins.

A 1975 California Department of Water Resources study of egg survival and fry emergence furnishes information on the emergence capability within various spawning gravel materials (California Department of Fish and Game 1977). The study compared egg survival and emergence of chinook salmon in several artificial redds (spawning sites) constructed of materials obtained from Grass Valley Creek. The survival of implanted chinook salmon eggs was examined after hatching had ceased. The investigation suggested that egg survival is affected more by the presence of fine sand, but that coarse sand (>0.83 mm) like that in the bedload of Grass Valley Creek affects the emergence of fry.

It is the problem of fry emergence that is particularly apparent in the Trinity River. The typical composition of unrestored riffles in 1979 differed substantially above and below Grass Valley Creek, which is the primary source of coarse granitic sands; the downstream percentage of coarse sands was twice (28%) that upstream (Frederiksen and others 1980).

The crevices within the gravel and cobble bed mate-

Table 1. Estimated accumulated sediment over a 9.3-km (5.8-mi) reach between Grass Valley Creek and Steel Bridge (adapted from Strand 1981).

Size class (mm)	Distribution by subreach (%) 1	2	3	4	5	6	7	8	9	Tonnage (MT)
0.06–0.5	20	11	7	10	6	9	12	32	28	8800
0.5–1.0	18	14	12	16	19	23	25	42	21	12,350
1.0–2.0	20	24	47	23	33	41	31	22	25	17,025
2.0–4.0	19	28	22	33	35	24	26	4	16	13,250
4.0–8.0	12	17	11	16	7	3	6	0	4	4700
8.0–16.0	11	6	1	2	0	0	0	0	6	1600
Tonnage (MT)	4650	8975	4600	4575	4975	9025	7100	6125	7700	57,725

rial are an essential form of cover for young fish, necessary for successful rearing because they protect the fry from predators and turbulent flows. In natural stream systems, occasional extreme peak flows occur with sufficient energy to move the gravels and cobbles, releasing the trapped fines. Because these natural flushing flows are eliminated below Lewiston Dam, the gravel interstices throughout much of the Trinity from Old Lewiston Bridge to the North Fork have filled with sand, thereby decreasing the cover for fry.

Where gravel is rarely or never moved by flood flows, sand, silt, and clay accumulate in the voids and become compacted and armored over by larger material. Algal growth, stimulated by nutrients in septic tank effluents from housing development, has occurred on the fine sediments in the Trinity and caused fine silt and clay to collect and form a cemented layer or crust. It is impossible for juvenile fish to find cover or overwinter in this substrate, and spawning is greatly reduced.

Sedimentation and compaction also have adversely affected the production of fish food organisms. Benthic invertebrates require small interstices between gravel for shelter from high water velocities and cannot survive and reproduce without this habitat. Newly emerged and small fry that drift into these areas are the most affected, as a shortage of food limits their survival; large fish have the ability to move through the barren area to a feeding site. Invertebrate production could become reestablished if the intruded fines are removed.

Eliminating the regular recurrence of large flood flows from rain and snowmelt in the mainstem Trinity River also has increased the size of the deltas at the mouths of most of the tributaries that yield a heavy sand bedload. In fact, tributary streamflows downstream of Lewiston Dam often exceed the mainstem flows during heavy storm runoff, thereby further promoting delta expansion. The increased delta size has varying effects upon the fisheries: constricting the channel and raising the bed of the river causes ponding upstream, which may increase holding habitat for adult fish; at the same time, upstream riffles are flooded, making them unsuitable for spawning and invertebrate production.

From 1971 to 1978, when gravel was removed to decrease the size of the delta formation at Indian Creek, the delta had elevated the mainstem streambed approximately 1.8–2.4 m (6–8 ft) and had caused 900 m (3000 ft) of downstream bed aggradation, as well as 450 m (1500 ft) of upstream ponding (Frederiksen and others 1980). Deltas, like log jams, beaver dams, and other physical obstructions, can halt or slow the upstream or downstream passage of adult anadromous fish.

Flushing Flow Criteria

In general, the habitat needed for successful spawning and egg incubation for all anadromous fish must meet conditions of water depth and velocity, size of substrate, temperature, and other factors required by each species. The survival rate of eggs has been found to be closely related to the gradation of the bed material. The gradation must provide for sufficient flow exchange between the stream and gravel to provide the buried eggs with oxygen and remove metabolic wastes.

Tappel and Bjornn (1983) found in laboratory tests that 90%–93% of the variability in survival to emergence for salmonid embryos was correlated with changes in spawning gravel size composition. McNeil and Ahnell (1964) state that salmonid embryo survival is drastically reduced when fine sediments (<0.83 mm) in the spawning gravel exceed 20% of the total substrate volume. Chevalier and colleagues (1984) concluded that, in general, productive redds are no more than 5% fines sized 0.8 mm and smaller; nonproductive redds are 30% or more fines.

According to Frederiksen and associates (1980), these fines compose 8% of the spawning beds in the Trinity reach below Grass Valley Creek, indicating that no serious problem with embryo survival is likely. Strand (1981) reported that measured fine sediments <1.0 mm below Grass Valley Creek ranged from 19% to 74%, although these proportions are for an entire subreach of about a kilometer (several thousand feet), on average, and not strictly over the riffle beds (Table 1).

In gravels containing large amounts of fine sediment <0.85 mm, many of the salmon fry studied emerged before yolk sac absorption was complete, with diminished size and swimming ability and with greater susceptibility to predation. Studies by Reiser and White (1980) suggest that sediment accumulation during early embryonic development (precirculatory stage) may result in higher egg mortalities.

The gravel interstices of the redd must allow for the emergence of fry after hatching; excessive fines in the gravel can entomb alevins and fry, as can gravel compaction after spawning. Sediments approximately 1–3 mm in diameter will block the emergence of fry (Garvin 1974). Trinity River riffles below Grass Valley Creek possess a high proportion of fines in this range, occurring as coarse granitic sand. For example, Strand (1981) recorded a range of 26%–69% of fines 1.0–4.0 mm in the overall bed material in this reach (Table 1). A flushing flow must reduce this size fraction substantially to be successful.

Rearing of newly emerged fry and juveniles entails different habitat requirements. After hatching, the alevins or sac fry (young still attached to their yolk sac) lie in the gravel until the yolk sac is fully absorbed. Then they emerge to feed on plankton and small insects, moving into slower, shallower water near the streambank and away from predators.

Crouse and others (1981) concluded that the stream-rearing habitats of salmonids must provide protection from a high proportion of excessively fine sediments. Their experiments showed significant decreases in fish production in streams with gravels 80% and 100% embedded with fine sediments (2.0 mm or less) approximating 26% and 31%, respectively, of the total volume of substrates. Strand (1981) measured fines in this range composing 49%–96% of the substrates by weight in nine subreaches below Grass Valley Creek (Table 1); however, the percent of embeddedness was not reported.

Holding or resting habitat is usually provided by deep pools. Depth, temperature, and velocity are major factors in assessing the condition of holding habitat. The reduced velocity and lower temperature of deep pools aid in providing rest, and holding pools should offer protection against predators. Fish usually avoid shallow pools covered with light-colored sand in order to reduce their visibility to predators. The absence of pools suitable for holding habitat for adult salmonids limits the numbers of adults surviving to spawn and so may limit fish production as well. Because previous average pool depths of 3–6 m (10–20 ft) along the Trinity below Lewiston have filled to depths of 1–2 m (3–6 ft), a successful flushing flow (or alternative management measure) must restore and maintain streambed pools.

Sediment deposition in pools can reduce habitat available for summer rearing as well as for overwintering. The conditions imposed in the winter can be especially taxing since many juvenile salmonid species reside in the intergravel spaces of the substrate. Bjornn and others (1977) and Stuehrenberg (1975) added sediment <6.4 mm in diameter to natural stream channels and found juvenile salmon abundance declined in almost direct proportion to the amount of pool volume lost. Stowell and others (1983) and Kelley and Dettman (1980) have used ratings of substrate embeddedness for assessing summer rearing and winter carrying capacity, based on empirically developed relationships between embeddedness and fish densities.

Conveyance or migration habitat provides the means for transport to and from the sea, so the river must be free of any barriers that either physically halt the fish, such as a delta formation, or cause their avoidance; high temperature, turbidity, and suspended sediment concentrations can delay upstream migration. Juveniles usually migrate seaward in the spring on increasing runoff flows, which may provide them with protection from predators, allowing them to drift with the current and so conserve energy.

The US Fish and Wildlife Service (1980a) has developed velocity, depth, and substrate preference curves for spawning, juvenile, and adult stages of Trinity River chinook salmon and steelhead trout. The curves are used with instream flow incremental methodology (IFIM) computer modeling to estimate the habitat available for each life stage of each species under different flow regimes. Habitat requirements drawn from the general literature can be compared with the limits on the preference curves (Table 2).

Temperature and water velocity criteria from the literature are omitted from Table 2 since these are not particularly susceptible to management through flushing flows. It should be noted, however, that adverse

Table 2. Substrate size and water depth criteria applicable to flushing flows for chinook salmon and steelhead trout habitat (various sources).

Parameter	Life stage	Species	Criteria	Source
Substrate size	Spawning/incubation (riffles)	Chinook salmon	3–100 mm (0.12–4.0 in.)	Thompson and Fortune (1970)
			4–10 mm (0.16–0.4 in.)	USFWS (1980a)[a]
		Steelhead trout	30–75 mm (1.2–3.0 in.)	Thompson and Fortune (1970)
			4 mm (0.16 in.)	USFWS (1980a)
	Juvenile rearing	Chinook salmon	2–175 mm (0.8–7.0 in.)	USFWS (1980b)
			3–175 mm (0.12–7.0 in.)	USFWS (1980a)
		Steelhead trout	124–173 mm (4.9–6.8 in.)	Bustard and Narver (1975)
			270–330 mm (10.6–13.0 in.)	USFWS (1980b)
			130 mm minimum (5.1 in.)	USFWS (1980a)
	Adult resting/holding (pools)	Chinook salmon	0.06–4000 mm (0.002–158 in.)	USFWS (1980b)
			No preference	USFWS (1980a)
		Steelhead trout	0.06–220 mm (0.002–8.7 in.)	USFWS (1980b)
			0.06–175 mm (0.002–7.0 in.)	USFWS (1980a)
Water depth	Spawning/incubation (riffles)	Chinook salmon	23–107 cm (9–42 in.)	Bell (1973)
			23–38 cm (9–15 in.)	USFWS (1980b)
			30–38 cm (12–15 in.)	USFWS (1980a)
		Steelhead trout	30–43 cm (12–17 in.)	Sams and Pearson (1963)
			15–76 cm (6–30 in.)	Fortune and Thompson (1969)
			30 cm (12 in.)	USFWS (1980a)
	Juvenile rearing	Chinook salmon	30 cm preferred (12 in.)	USFWS (1980b)
			30 cm minimum (12 in.)	USFWS (1980a)
		Steelhead trout	8–36 cm (3–14 in.) for brood class; 36–81 cm (14–32 in.)	USFWS (1980b)
			36 cm minimum (14 in.)	USFWS (1980a)
	Adult resting/holding (pools)	Chinook salmon	1.9 m preferred (6.3 ft)	USFWS (1980b)
			>2.4 m preferred (8 ft)	USFWS (1980a)
		Steelhead trout	61 cm preferred (24 in.)	USFWS (1980b)
			61 cm minimum (24 in.)	USFWS (1980a)
	Upstream migration	Chinook salmon	24 cm minimum (9.6 in.)	Thompson (1972)
		Steelhead trout	18 cm minimum (7.2 in.)	Thompson and Fortune (1970)

[a] US Fish and Wildlife Service IFIM habitat preference curves.

temperature changes are generally a function of reduced stream depth, particularly in pools. Also, excessive near-shore velocities result from steepening of banks caused by decreased streamflows and the encroachment of riparian vegetation. According to the US Fish and Wildlife Service (1980a), feathering or tapering of streambanks is important to improve juvenile chinook salmon habitat, as they require the slow velocities (flows under approximately 4 m^3/s or 150 cfs) that are provided by tapered streambanks.

The relationship of pools and riffles in a salmonid environment is critical to spawning and fish production. In order for a riffle to serve as spawning habitat, the velocity and depth of streamflow must meet the requirements for the species. The number and overall length of pools and the slope of a reach greatly affect the water velocity over a riffle. Most salmonids spawn at the head of the riffles (or ends of pools), where the smooth water breaks into the riffle. Fish production is highest in streams with a pool-to-riffle ratio of approximately 1:1; the range for the optimum ratio is 0.5:1 to 3.5:1 (Fortune and Thompson 1969). The filling of pools in the Trinity streambed probably has reduced this ratio well below the optimum, but reliable data are lacking.

A number of aquatic ecological characteristics limit the timing of flushing flows; flow timing should be based on the life history requirements of important fishes in a system. Peak flows produced by rapid increase and decrease in dam releases can dislodge and transport eggs and alevins, can dewater redds constructed during a prolonged flushing flow, can strand fish in side pools that are isolated as flows recede, and can increase the incidence of catastrophic invertebrate drift (Reiser and others 1985).

Flushing flows released prior to spawning should effectively remove fine sediments from spawning gravels while reducing egg and alevin mortality. It may be possible for correctly scheduled flushing flows to serve a dual purpose by also transporting smolts downstream. The most beneficial timing will vary with the Trinity River target species: April through August for chinook salmon between fry emergence and spawing of adults; August through January for steelhead trout.

Flushing Flow Methodology

The methodological objective is to determine the magnitude and duration of flow necessary for one-time channel restoration and for periodic maintenance of the restored channel (or a smaller, readjusted channel). There is no standard methodology, but a comparison of all available techniques and their assumptions is beyond the scope of the case study. The techniques used in this case will illustrate the available methodology.

A prediction of flushing flow requirements generally calls for a standard set of inputs: channel geometry (representative widths, depths, and cross sections); length and slope of the target stream reach; surface area, tonnage, and particle-size distribution of channel-bed materials and sediment deposits; width, depth, velocity, and water surface elevations at selected cross sections for various stream discharges; suspended sediment concentrations and bedload quantities at selected cross sections for various stream discharges; total sediment discharge from tributaries and erosion from channel banks; and the regime of tributary inflows.

Bed material sampling of Trinity stream riffles in the 16-km (10-mi) target reach between Grass Valley Creek and Indian Creek during June 1979 verified the heavy accumulation of sand embedded in the riffle gravels. Flows of sufficient magnitude and duration that are released from Trinity Reservoir (Claire Engle Lake) and passed through the smaller Lewiston Lake, the reregulating reservoir (Figure 1), could mobilize the riffle gravel, allowing the embedded, compacted sand to flush out of the target reach.

Frederiksen and associates (1980) used the Gessler (1970) method to calculate the flows necessary to move the gravel below Grass Valley Creek. However, this method does not take into account the degree of compaction of the embedded sand. With this method, it must be assumed that a sand-embedded gravel bottom, especially one with a cemented crust formed by algae binding silt and clay, would require mechanical loosening before a flushing flow could succeed.

The Gessler method determines the probability of a particular bed-size distribution remaining stable at a selected flow size, based on comparing the local shear stress acting on an individual grain with its critical shear stress. The critical stress is that hydraulic force upon a particle when it begins to move (incipient motion). The stability of the bed material is accounted for as a function of the maximum and minimum grain sizes of the bed sediment and of the grain-size distribution of the stable armor layer.

A family of curves was developed by Frederiksen and associates (1980), based on the Gessler equations, for computing the flow necessary to disturb the riffle gravels in the 16-km (10-mi) target reach. For a given particle-size distribution and channel slope, the bed becomes increasingly unstable (approaching movement) and the stability coefficient decreases as the discharge, flow velocity, and depth of flow increase.

With a riffle-bed slope of 0.0025 and a bed stability coefficient of 0.4 that would ensure an unstable condition (<0.5 indicates instability), the predicted minimum flow for incipient motion of the gravel is 1.7 m^3/s per meter of stream width (18 cfs/ft). This rate of flow would produce a flushing velocity of 1.7 m/s (5.6 fps) with a flushing flow depth of 1 m (3.3 ft). Thus, a

15.0-m-wide (50-ft-wide) riffle in the target reach would require a flow of 25 m³/s (900 cfs) and a 22.5-m-wide (75-ft-wide) riffle would necessitate 38 m³/s (1350 cfs). The substrate-size distribution for this calculation ranges from 4.76 to 75.0 mm, including fine and coarse gravel and cobble materials. Before stream regulation, these flows occurred an average of at least 48% and 42% of the time, respectively.

The Gessler method was applied to calculate the flushing flow needed to remove embedded fines from spawning riffle gravel as a periodic maintenance measure. However, the filling of steambed pools important to rearing of juveniles and holding of adults in the target reach is of equal concern. To determine the practicality of a flushing flow for the periodic removal of surplus sand deposits (<4.76 mm) throughout the streambed, it is necessary to know the annual sand budget for the target stream reach. Frederiksen and associates (1980) estimated the average annual sand inflow into the reach by estimating the sediment discharge from the upstream tributary watersheds (primarily Rush Creek and Grass Valley Creek).

Estimates were based on sediment discharge data for nearby gaged streams and on a small amount of data for Grass Valley Creek. The average sand inflow was estimated at 82,900 MT/yr (91,200 tons/yr) under existing conditions, which could be reduced to 4145 MT/yr (4560 tons/yr) by assuming extensive watershed management and a sediment dam on Grass Valley Creek. The sand discharge capacity was estimated for preproject and postproject conditions, assuming annual reservoir releases of 250, 320, and 390 × 10⁶ m³ (200,000, 260,000, and 320,000 ac-ft).

The discharge capacities were calculated from flow-duration curves and from a set of curves developed using the Laursen Formula (Vanoni 1975), which express sand discharge as a function of water discharge for three different hydraulic conditions: stream riffles, stream runs with less-than-average gradient (filled-in pools for the most part), and pools. The Laursen-derived curves provide the sand discharge rate for a particular stream discharge, depending on certain channel widths and slopes. In calculating the sand discharge capacity, a maximum instantaneous reservoir release of 25 m³/s (900 cfs) was assumed to protect the riffle gravel immediately below Lewiston Dam from displacement.

The results indicate that for annual reservoir releases of 390 × 10⁶ m³ (320,000 ac-ft), the 9-m-wide (30-ft-wide) pools below Grass Valley Creek would have a sand discharge capacity of 20,200 MT/yr (22,200 tons/yr); 420 × 10⁶ m³ (340,000 ac-ft) was adopted for the ultimate schedule. At this rate, these pools would be kept free of sand, *assuming the adoption of intensive watershed management practices.* However, the 18-m-wide (60-ft-wide) pools would have the capacity to discharge only 1690 MT/yr (1860 tons/yr) and therefore would gradually fill, even with intensive watershed management. The calculations also indicate that the riffles would be kept sand free with reservoir releases of 250 × 10⁶ m³ (200,000 ac-ft) or more.

Intensive management to reduce soil erosion and stream sedimentation is assumed to carry a potential to reduce the annual sediment yield from 1100 MT/km² (3150 tons/mi²) to 120 MT/km² (350 tons/mi²). Less than 35 MT/km²/yr (100 tons/mi²/yr) of sediment yield is believed to be normal for *undisturbed* watersheds with comparable terrain, soil composition, and forest cover in Idaho and Oregon (Megahan 1979).

In contrast to the annual riffle and pool maintenance flushing flows evaluated by Frederiksen and associates, a one-time remedial flushing flow to remove the great accumulation of sand from the riverbed was estimated using another methodology. During 1979 and 1980, the Hydrology Branch of the US Bureau of Reclamation's Engineering and Research Center conducted studies to predict the magnitude and the duration of flows necessary to remove various size classes of sediment deposits from the entire reach of the Trinity River between Grass Valley Creek and the Steel Bridge 9.3 km (5.8 mi) downstream (Strand 1981).

The predicted requirements for remedial flushing are based on suspended sediment and bed material samples, channel cross-section measurements, water-surface elevation projections, and hydraulic measurements made in the target reach at controlled flows of 8.5, 17, and 62 m³/s (300, 600, and 2200 cfs). Total sediment discharge in the reach was computed from suspended sediment data, bed material samples, and hydraulic measurements for each of these flows, using the modified Einstein method (Colby and Hembree 1955). Comparable calculations were made using several other sediment transport equations that required only bed samples and hydraulic values as input data.

The results obtained using the velocity-xi equation (Pemberton 1972) gave the closest fit to the results obtained using the modified Einstein method. The velocity-xi equation, a modification of the Einstein bedload function that was based on extensive experimental data (Einstein 1950), was then used to predict total sediment transport for higher flows for which no suspended sediment data were available.

Strand (1981) divided the study reach into nine subreaches, each represented by 1–4 cross sections. The amount of each size fraction of sediment in each subreach was roughly estimated from bed material samples and from field observations at the transect sites (Table 1). The amount of sediment in each size class remaining in each subreach after specified flushing durations at various stream discharge intervals was calculated using the velocity-xi equations as part of a computer program called PSANDS; water surfaces at different flows were calculated for each cross section using the PSEUDO computer program (Strand 1981).

A family of curves was developed that showed the tonnage and volume (m^3 or yd^3) of each size fraction (<2.0 mm, 2.0–4.0 mm, 4.0–8.0 mm, 8.0–16.0 mm) that would be removed from the total study reach at different flow magnitudes (m^3/s or cfs) and durations (days) (see Figure 3 for an example). The durations required for 50% and 90% removal of the different size fractions of sediment, at discharges of 57, 113, 170, and 283 m^3/s (2000, 4000, 6000, and 10,000 cfs) were calculated (Table 3), along with the reservoir storage allocations (m^3 or ac-ft) and water use efficiency (%). Efficiency values are based on a flushing flow of 283 m^3/s (10,000 cfs) being defined as 100% efficient.

For example, 90% removal of fine sediment (<2.0 mm) can be accomplished by flushing for 28.5 days at 113 m^3/s (4000 cfs) or for 14.5 days at 170 m^3/s (6000 cfs). The corresponding reservoir allocations and efficiencies are 279×10^6 m^3 (226,100 ac-ft) at 70% and 213×10^6 m^3 (172,600 ac-ft) at 92%, respectively. The percent removed in the troublesome 2.0- to 4.0-mm size fraction would be considerably less than 90% unless the more damaging 170- or 283-m^3/s (6000 or 10,000-cfs) flushing flow is used. The removal of each size class of sediment is averaged over an entire subreach 600–1400 m (2000–4700 ft) long; removal in riffles would, of course, be proportionately greater than in deep pools.

Reservoir releases predicted to cause movement of riffle gravels or to flush sediment from pools or from an entire reach could be timed to coincide with peak tributary inflows, thereby demanding less reservoir storage to be allocated to flushing operations. The highest peak flows of Grass Valley Creek and Rush Creek occur during January through April. Coordination of reservoir releases with tributary peaks to augment flushing flows would depend on the compatibility of a flushing flow with other fishery requirements during these months, and on the degree of flexibility and responsiveness of reservoir operations.

Mean monthly flows for Grass Valley Creek and Rush Creek during February, the month of highest flow, are on the order of 2.8–5.7 m^3/s (100–200 cfs).

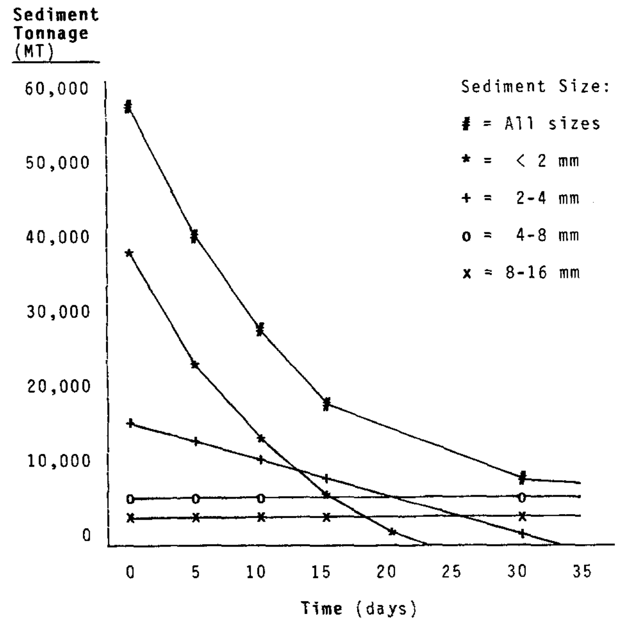

Figure 3. Sediment remaining in place over time during flushing–scouring flows of 170 m^3/s (6000 cfs) in the Trinity River below Grass Valley Creek, (Strand 1981).

Therefore, any significant augmentation would require careful coordination to take advantage of peak storm flows. This strategy is much more relevant to lower-level maintenance flushing rates 25–38 m^3/s (900–1350 cfs) than to very high remedial flushing rates (113–283 m^3/s or 4000–10,000 cfs); tributary inflows would augment the higher flushing flows very little.

Impact Mitigation

The presence of sediments embedded in the gravel has been determined as the primary cause of reduced fish production. Sediments have accumulated as the result of accelerated sand discharge from eroded tributary watersheds and the greatly diminished river flows due to regulation by Trinity and Lewiston Dams. Time-series data to support a study of riffle material composition over time are unavailable, but recorded observations and aerial photographs document the great excess of sediments, particularly coarse sands, over normal conditions.

While the emphasis in the case study is on the efficacy of artificial flushing flows, only a comprehensive instream sediment management strategy could be expected to mitigate the severe impacts. In 1983, the Trinity River Fish and Wildlife Task Force adopted a complete management program encompassing 11 ac-

Table 3. Sediment removal efficiency for flushing–scouring operations below Grass Valley Creek (Strand 1981).

	50% Removal			90% Removal		
	Flow duration (days)	Flow volume $\times 10^6$ m^3 (ac-ft)	Water use efficiency (%)	Flow duration (days)	Flow volume $\times 10^6$ m^3 (ac-ft)	Water use efficiency (%)
113 m^3/s (4000 cfs)						
Total	18.0	176 (142,800)	58	—	—	—
<2.0 mm	14.2	139 (112,700)	49	28.5	279 (226,100)	70
2–4 mm	25.0	245 (198,400)	114	45.3	443 (359,410)	113
170 m^3/s (6000 cfs)						
Total	9.2	135 (109,500)	76	35.6	523 (423,700)	103
<2.0 mm	6.5	95 (77,400)	72	14.5	213 (172,600)	92
2–4 mm	17.9	263 (213,000)	106	32.5	477 (386,800)	105
283 m^3/s (10,000 cfs)						
Total	4.2	103 (83,300)	100	22.0	538 (436,400)	100
<2.0 mm	2.8	68 (55,500)	100	8.0	196 (158,700)	100
2–4 mm	11.4	279 (226,100)	100	20.5	502 (406,600)	100

tions to achieve fishery management goals; two of these actions specifically pertain to instream sediment management (US Fish and Wildlife Service 1983):

- Control sediment inflow from Grass Valley Creek by building a debris dam near the mouth of the creek and establish a sand dredging system in the Trinity River below the creek confluence to remove past accumulations. In a related action, rehabilitate the Grass Valley Creek watershed to extend the useful economic life of the dam.
- Rehabilitate and maintain the mainstem streambed below Lewiston by disturbing compacted sediments, replacing depleted gravel, and removing encroaching vegetation. Maintain channel characteristics to provide habitat for spawning, rearing, holding, and conveyance consistent with the adopted production goals.

Sediments dredged from the Trinity will be used to rehabilitate barren gravel mine tailings along the river, which will improve riparian and upland habitat in addition to improving stream habitat.

Alternatives to impounding sediment behind a dam and dredging sand in the mainstem river included: alternative dam sites, the use of settling ponds, reliance on suction dredging or dam construction alone, and large releases from Lewiston Dam to flush granitic sand from sites of deposition below Grass Valley Creek. Alternatives to streambed habitat rehabilitation in the mainstem river included: large flushing flows to clean gravel beds and increased hatchery production to supplement natural spawning.

The Task Force unanimously adopted the preferred actions, *excluding* the flushing flow alternatives; the proposed sediment dam was authorized for construction and initial funding of advanced dam design work and sand dredging was approved for federal fiscal year 1983 (US Fish and Wildlife Service 1983). The use of flushing flows was deemed extremely expensive by the Task Force, particularly in terms of lost hydroelectric generation and irrigation water supply, and flushing flows could endanger residents who have moved into the floodplain after the construction of the dam. Also, it was believed that existing fish habitat could be damaged or made unusable during extended flushing flows.

For example, the velocity-xi methodology indicated that to provide one-time *remedial* scouring-flushing flows at 113–283 m^3/s (4000–10,000 cfs) for 8–28 days to remove 90% of fines <2.0 mm from stream runs and pools would require about 195–280 $\times$ 10^6

m^3 (159,000–226,000 ac-ft) (Table 3) or 16%–23% of the firm annual yield of reservoir diversions for irrigation and hydropower production.

In contrast, an annual *maintenance* flushing flow of approximately 40 m^3/s (1500 cfs) was recommended, using the Gessler formula based upon a flow rate of 25–38 m^3/s (900–1350 cfs) and a velocity of 1.7 m/s (5.6 fps) for incipient motion of gravel below Grass Valley Creek in riffles 15–22.5 m (50–75 ft) wide and 1 m (3.3 ft) deep. This flushing operation would call for as little as 7.4×10^6 m^3 (6000 ac-ft), or less than 1% of the firm yield. Subsequently, a one-third greater magnitude of 57 m^3/s (2000 cfs) was suggested as a margin of certainty, requiring 25×10^6 m^3 (20,000 ac-ft) (VTN Environmental Sciences 1979).

The latter requirement assumes a range of 2–5 days to remove an annual surface accumulation of sediment from spawning riffle gravel, once the heavy deposits present are removed mechanically or hydraulically. The formally adopted new schedule of reservoir releases for Lewiston Dam, another action designed to implement the managment program, allows for 40×10^6 m^3/yr (32,000 ac-ft/yr) of contingency releases, including fish conveyance and sediment flushing purposes (US Fish and Wildlife Service 1980a and b).

Summary and Conclusions

The least damaging one-time remedial scouring–flushing flow rate of 113 m^3/s (4000 cfs) with an average velocity of 1.9 m/s (6.1 fps) over 28 days would demand 279×10^6 m^3 (226,000 ac-ft) of reservoir storage to remove 90% of the accumulated fine sediments (<2.0 mm) below Grass Valley Creek, assuming an average stream width of 27 m (87 ft) and a 2.2-m (7.3-ft) average depth. This flow is large enough to simulate the historical peak flows below Grass Valley Creek that are necessary to move large cobbles, to destroy the annual growth of bank vegetation, and to restore the approximate original channel configuration.

The recommended large scouring–flushing flow would remove virtually all accumulated sand on the riffle gravel, including surficial, embedded, and cemented deposits, resulting in restoration of spawning–incubation habitat and of benthic invertebrate production in the stream riffles. However, heavily armored sand deposits could require mechanical disturbance of bed materials first, and flushing of the coarser sands (2.0–4.0 mm), which present a problem for emerging fry, would be limited to little more than 50%.

Unavoidably, the adverse effects of this remedial scouring–flushing operation tend to offset the benefits. Sustained flooding of riffle beds and depletion of riffle gravel below the dam would be expected to cause a major loss of the food, cover, and reproductive values that have developed in the postproject adjusted channel.

In terms of direct economic impact, the extreme depletion of storage capacity and limits on the diversion of allocated irrigation and hydroelectric water supplied could seriously compromise Central Valley Project repayment contracts. The least damaging 113-m^3/s (4000-cfs) flow, displacing 23% of the firm annual yield (1230×10^6 m^3 or 1,000,000 ac-ft) of Lewiston Reservoir, could possibly require renegotiation of contracts during the year of remedial scouring and flushing.

Annual maintenance flows of sufficient magnitude to move the riffle-bed material and to entrain surficial sand and silt would call for releases from Lewiston Dam of approximately $7.4–25 \times 10^6$ m^3 (6000–20,000 ac-ft) at 40–57 m^3/s (1500–2000 cfs) below Grass Valley Creek. Ideally, flushing releases would be synchronized with periods of peak tributary inflows to minimize the allocation of reservoir storage. However, with the present compacted condition of many riffles, extensive streambed rehabilitation would first be necessary to ensure successful annual maintenance flushing flows.

Other prerequisites are attached to the success of an annual maintenance flushing flow:

- Construction of the sediment dam and storage reservoir on Grass Valley Creek to remove virtually all sediment discharge to the mainstem river over 20–150 years (the length of time depends on the degree of success of Grass Valley Creek watershed management programs, particularly the revegetation and stabilization of steep slopes and streambanks).
- Dredging of sand deposits that are burying the river gravel, mechanical loosening of embedded and cemented sand-gravel substrate, and replacement of depleted gravel prior to initial maintenance flushing flow.

A maximum 95% reduction in sand discharge below Grass Valley Creek, to 4145 MT/yr (4560 tons/yr), is expected with optimum erosion control in the Rush Creek watershed, assuming a maximum potential reduction in soil erosion from 1100 to 120 $MT/km^2/yr$ (3150 to 350 $tons/mi^2/yr$) and virtually total sediment impoundment on Grass Valley Creek. Thus, virtually complete removal of accumulated sand, including surficial, embedded, and cemented deposits on riffle gravel, is expected to restore spawning–incubation habitat and the benthic invertebrate production of stream riffles.

On the negative side, annual releases of 40 m^3/s (1500 cfs) could cause permanent coarsening of some riffle segments in the uppermost reach below the dam, requiring periodic replenishment of gravel. Also, releases during the spawning season would be harmful, as anadromous fish spawning is most successful at velocities of 0.5–0.8 m/s (1.5–2.5 fps). Finally, a sediment control dam is a barrier to upstream migration in Grass Valley Creek, thus assuring some loss of spawning habitat along that tributary.

Flushing flows for pool maintenance could not be initiated until a substantial amount of excess in-channel sediment has been removed by mechanical or hydraulic dredging between Lewiston Dam and Indian Creek. The use of controlled large flows to cleanse the pools of sediment in their present state is considered beyond any feasibility.

The magnitude and duration of flows required to scour and flush pools that are currently 0.9–1.8 m (3–6 ft) deep to a restored depth of 3–6 m (10–20 ft) would cause extensive damage to floodplain settlements and would permanently damage the uppermost riffle beds. As sediment control programs on the tributaries become more successful, dredging operations to restore the streambed pools should become more effective. It has been suggested that pools for adult holding and juvenile rearing be developed and then protected by maintenance dredging every five years.

Remedial scouring–flushing flows would remove up to 90% of fine sand and silt (<2.0 mm), or 38,200 MT (42,000 tons), from the target reach below Grass Valley Creek, plus about 50% of coarser sands (2.0–4.0 mm), or 13,200 MT (14,500 tons). These projections are averaged for riffles, runs, and pools; the higher-than-average flushing velocities over riffle beds are expected to make them sand free. The percent removal in pools would undoubtedly fall short of 50% and the remedial effects would be less than are needed to restore the rearing, resting, and holding habitat needed for survival and migration. However, a second season of remedial high flows might nearly attain that objective.

With a maintenance flushing flow, it is estimated that virtually all removal of fine sand and silt (bed material <2.0 mm) would result from annual maintenance flushing flows, except in pools wider than 9 m (30 ft). Assuming reservoir releases of 395×10^6 m^3/yr (320,000 ac-ft/yr), the sand discharge capacity of 18-m-wide (60-ft-wide) pools is estimated at 1690 MT/yr (1860 tons/yr), but the required capcity is estimated at 4145 MT/yr (4560 tons/yr). The surplus sand and accumulated gravel and cobbles must be removed by periodic maintenance dredging. The remedial effects with a maintenance flow would extend to the restoration of rearing, resting, and holding habitat in streambed pools needed for fish survival and migration.

Both the remedial and maintenance flow releases provide for the suppression of riparian vegetation to prevent channel encroachment and to maintain tapered slopes with low-velocity, shallow-water nursery habitat, but both would require mechanical removal of mature growth before scouring–flushing operations. The remedial high flows would be sufficient to move the large cobbles and destroy the new annual growth of vegetation, but the magnitude of such flows would severely damage the housing settlement within the floodplain, so in this instance it is necessary to use mechanical means to remove riparian growth.

Both remedial and maintenance flows also provide for restoration of channels free of delta formations through dredging or channelization; periodic maintenance dredging is necessary with an annual flushing flow. The expected remedial effects are the improvement in local habitat and fish passage because of eliminating upstream ponding and downstream channel aggradation. Displacement of delta formations out of the target reach by means of flow modifications at Lewiston Dam would be impractical; flows of the necessary magnitude would severely damage floodplain development and destroy spawning riffles in the upper reaches below the dam by removing gravel.

The liabilities of releasing mammoth scouring–flushing flows approximating a preproject magnitude make this option unviable. Offsetting damage to fish habitat established under the postproject streamflow regime, as well as damage to human settlements in the floodplain, would be unacceptable, as would the opportunity costs to water users in the Sacramento River Valley. However, the technical feasibility of annual maintenance flushing flows seems assured, although the cost effectiveness of a sediment control dam with a limited useful economic life, combined with perpetual maintenance dredging, seems dubious.

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