Sacramento River Ecological Flows Study:
Gravel Study Final Report

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EXECUTIVE SUMMARY

The gravel resources of the Sacramento River are fundamental to the river's aquatic and riparian habitat, and they are particularly important for salmonids. Along the remaining salmonid spawning reaches of the Sacramento River, human activity has extensively altered the river's flow and sediment regimes, which are key regulators of the extent and quality of spawning gravel in the mainstem. As an initial step toward conserving the river's salmon and other aquatic and riparian resources, it is important to understand the current condition of gravel resources and how human activities have affected their quality, transport and extent. This report addresses these issues by synthesizing existing information and analyzing data from a new field study, conducted in 2005 and 2006.

The Sacramento River gravel study is a component of the Sacramento River Ecological Flows Study, which is being led by The Nature Conservancy (TNC) with funding from the CALFED Ecosystem Restoration Program (CALFED grant ERP-02D0P61) and the Resources Legacy Fund Foundation. Key objectives of the gravel study were to (1) refine estimates of the flow required to mobilize and scour the bed surface, (2) characterize gravel and its habitat value for salmonids, and (3) provide data for application of The Unified Gravel-Sand (TUGS) model, a new sediment transport model that can predict the evolution of grain-size distributions in the surface and subsurface of a channel bed.

The study design was guided by three working hypotheses that focus on characterizing changes in Sacramento River gravel resources, and identifying the causal mechanisms that drive such changes:

Hypothesis 1. The quantity of spawning gravel has been decreasing over time due to bed-surface coarsening associated with the effects of in-stream mining and dam-related reductions in sediment supply from headwater sources.

Hypothesis 2. Bed-surface coarsening has propagated progressively downstream from the dams.

Hypothesis 3. The quality of any remaining spawning gravel in the upper river has declined in concert with the river's ability to flush fine sediment from the subsurface of its bed, due to reduced surface mobility—a consequence of (i) coarsening and (ii) the reduced frequency and magnitude of peak winter floods.

We explored these hypotheses by quantifying trends in grain-size distributions, bed elevations, gravel permeability, and area used by spawning fish. Data sources included (1) results from TUGS sediment transport modeling, (2) historical results from previous studies, and (3) observations and measurements from a new field study.

Historical maps constructed from aerial surveys indicate that spawning area used by fall-run Chinook salmon declined substantially across much of the upper river from 1964 to 1980, except in the immediate downstream vicinities of the river's sediment-bearing tributaries. Our analysis indicates that, by 2005, spawning area had increased substantially in the uppermost reaches of the river, apparently due to locally beneficial effects of gravel augmentation. Spawning area had not, however, recovered in the stretch from Redding Riffle (RM 298) to RM 292 as of 2005. We estimate that the overall loss in spawning area was ~30% for the analyzed subreach (RM 302–290), from 1964 to 2005. Taken together, these observations are consistent with hypothesis 1, which suggests that. there have been marked losses in spawning area, except for small reaches downstream tributaries and gravel augmentation projects. This reduction in spawning habitat suggests that spawning gravel has been lost; it seems unlikely that changes in the flow regime between the surveys could affect local hydraulic conditions enough to cause such large-scale changes in spawning use. A key assumption in our analysis is that mapped spawning areas correspond to boundaries of all suitable spawning gravel during each survey. The assumption seems to be reasonable for the aerial surveys of 1964 and 2005, based on (1) field-based observations of redds in marginally suitable deposits during the facies mapping work in 2006, and (2) the fact that the estimated abundance of fall run spawners in 1964 and 2005 was greater than or equal to the estimated abundance for 2006 (when saturation of habitat by spawning salmon appears to have occurred).

Bulk samples exhibit a higher degree of armoring in the upper river, relative to the middle river, consistent with what we would expect to see if coarsening had increased surface grain sizes in the upper river (as proposed by hypothesis 1). However, wide scatter in median grain size (D_{50}) across the study reach indicates there is substantial natural variability in grain size at the scale of individual point bars. This may be one reason why we see no clear changes in median grain size of either the surface or subsurface from 1995 to 2005 in the upper river. As of 2005, both the surface and subsurface have proportionally more coarse gravel and cobble (and proportionally less fine gravel and sand overall) for two upper river sites where data from 1995 and 2005 overlap. This suggests a loss of relatively fine material from the subsurface (which would stand as direct evidence against hypothesis 3), but we are unable to identify the mechanism for it. Bulk sampling data from 1980 are incompatible with data from 1995 and 2005, due to differences in sampling methods. Bulk sampling data from 1984 are also not completely compatible with data from 2005 (due to differences in sampling methods) and otherwise could be taken to suggest that median grain sizes became slightly coarser by 2005 in both the surface and subsurface within the middle river.

Wolman counts show wide scatter in D_{50} across the study reach. This confirms there is substantial natural variability in grain size at the scale of individual point bars. Wolman count distributions agree remarkably well with data from bulk samples of the surface. This suggests that our Wolman counts provide a realistic assessment of the true (i.e., volumetric) grain-size characteristics of the surface. Our time-series of grain-size distributions suggest that changes in grain size are erratic, with coarsening at some sites and fining at others. This may simply reflect natural variability in grain size, coupled with imprecision in reoccupying sampling sites in successive field efforts. Statistical analysis shows that, as of 2005, median grain sizes were coarser, on average, than they were in previous years for the reach bounded by RM 298 and RM 283.5. This is consistent with hypothesis 1—that the quantity of spawning gravel has been decreasing over time. It is also consistent with hypothesis 3—that the quality of any remaining spawning gravel in the upper river has declined due to reductions in bed surface mobility. Statistical analysis shows that the dispersion in grain size distributions has become smaller over time for the reach bounded by RM 298 and RM 283.5. This implies that the increases in median grain size are the result from winnowing—the selective transport of relatively fine material (i.e., coarse gravel and fine cobbles) from sediment deposits.

Our facies mapping results highlight the potential importance of gravel augmentation, bank erosion, and tributary inputs as offsetting factors for the systemic, dam-related deficit in coarse sediment supply. They also highlight the importance of local hydraulics on the presence/absence of suitable spawning gravel. Importantly, results from the facies mapping exercise reveal the presence of redds in deposits that would be considered marginally suitable for spawning habitat at best. This implies that virtually all suitable spawning gravel was in use by the fall run during the mapping (a necessary condition for saturation in 2006, 2005, and, by extrapolation, 1964). Results also illustrate the potential for errors in mapping redds from the air; our field observations (from 2006) differ from what we mapped based on the 2005 helicopter survey, when fall run returns were similar in abundance—and thus presumably utilized a similar total area of spawning. At one site, spawning area declined progressively over time to just one-third of the total area mapped in 1964. Areas that no longer support spawning are covered by a coarse, immovable bed. This provides clear support for hypothesis 1 and, by extension, is consistent with hypothesis 3 as well. At another site—Redding Riffle—progressive losses of spawning area have occurred despite repeated additions of gravel. The fact that spawning fish are now apparently unable to break through the surface of the bed suggests that it has become coarser over time in concert with the spawning area losses; the coarse, immovable deposits must be relatively new, because Redding Riffle was once the site of some the river's most prolific Chinook salmon spawning. This is entirely consistent with hypothesis 1. When considered together across all five facies mapping sites, our observations support the working hypothesis that fall run Chinook salmon of the Sacramento River are not generally able to successfully spawn in deposits where more than 40% of the surface is covered by particles bigger than the largest movable particle—assumed to be 130 mm in b-axis diameter.

Permeability is higher at 6 inches depth than it is at the other measurement depths across all sites spanning the upper and middle river. For salmonids, this means that entombment and suffocation associated with infiltration of fine material into clean, newly built redds is unlikely to be significant over the course of a single, several-month-long, spawning-to-emergence period. This finding is inconsistent with hypothesis 3—that gravel quality has declined due to increased concentrations of fine sediment in the subsurface. However, permeability-based estimates of survival indices for our sites are almost universally poor. This would generally support hypothesis 3, but only if it applied specifically to the upper river, where coarsening has reduced bed mobility. This is not the case. Rather, permeability shows no clear trends with river mile, implying that it is no better or worse, on average, in the upper river. Overall, the permeability data are inconclusive with regard to the study hypotheses, due to the wide spatial variability in permeability and the lack of data on historical conditions.

The pattern of scour and stability implied by the scour chains and scour boxes is broadly consistent with more fossilized morphology in the upper and more dynamic mobility and change in the middle river. We identified two exceptions to this behavior. Both are consistent with local variations that would tend to overwhelm any broader tendencies toward stability or mobility. The pattern of scour and stability observed in this case is one of little surface mobility at sites where external sources of sediment supply are locally absent, and more significant scour and lateral change at sites where sediment supply and the observed frequency of morphologic change are relatively high. Although this does not clearly bear on any of the study hypotheses, it confirms the importance of taking the effects of local sediment sources into account in the assessment of spawning area changes over time. It also suggests that scour can be significant enough (>1 m) in the middle river to excavate redds, killing eggs and alevin if scouring flows occur during incubation. This could affect the fall run (the only race to use the scour-prone middle river for spawning) because they emerge in early winter when flows are periodically high enough to mobilize the bed.

Results from TUGS sediment transport modeling of the upper Sacramento River are broadly consistent with hypothesis 1—that the bed has been coarsening progressively over time, and hypothesis 2—that coarsening has propagated downstream progressively over time. For example, predicted median grain sizes increase sharply, by 80% within the first 20 years of the simulation at Redding Riffle, due to upstream-propagating effects of in-stream mining at Turtle Bay and downstream-propagating effects of reduced sediment supply from the dams. Further downstream, between RM 295 and RM 290, coarsening is more gradual, but nevertheless continuous, suggesting that grain size will probably continue to increase over time. The decrease in sediment storage between RM 295 and RM 290 reflects transport by successive high flows and the absence of supply from coarse sediment sources. In this reach, transport is generally dominated by selective removal of relatively fine material. This would lead to progressive coarsening with each successive bed-mobilizing event due to the absence of sediment supply. The predicted shift in the sediment rating curve for RM 294 is a direct result of coarsening; as grain sizes increase, bed mobility drops, reducing the amount of sediment carried by a flow of a given magnitude. This has implications for hypothesis 3, to the extent that a less mobile bed surface is generally prone to increases in fine sediment concentrations in the subsurface. However, results from sediment transport modeling are largely inconclusive about whether fine sediment concentrations in the bed are increasing, because rates of fine sediment supply are not well constrained along the river. For reliable estimates about changes in fine sediment concentrations in spawning gravel, TUGS would need rates of fine sediment inputs from bank erosion and agricultural runoff (from both diffuse and point sources). Ideally the data would span multiple years and would be broken up into piecewise contributions by river mile. In the absence of such data, results from TUGS are unable to definitively support or contradict hypothesis 3.

Taken together, the data and analysis from the gravel study are consistent in their support of hypothesis 1—that quantity of spawning gravel has been decreasing over time due to bed-surface coarsening associated with the effects of in-stream mining and dam-related reductions in sediment supply from headwater sources. Key lines of evidence include (1) the statistical analysis of the Wolman count data, (2) indications from changes in spawning area from 1964 to 2005, and (3) sediment transport modeling results. Evidence is particularly strong for the reach between RM 292 and RM 298, where facies maps of bed material size have been constructed. In other reaches, the picture is complicated by effects of potentially confounding sources of coarse sediment and other factors. It appears evident, however, that the reach between Keswick Dam and ACID has benefited substantially from gravel augmentation.

Grain size data from individual sites within the reach are inconclusive about whether coarsening is propagating downstream (hypothesis 2), due to the potentially confounding effects of spatial variability in grain size on sampled point bars. Moreover, our statistical analysis of the Wolman count data indicates that deposits have been progressively depleted of their fine and medium gravel over time, suggesting that coarsening is a broad-scale phenomenon that has been affecting the upper river as a whole (above RM 280) since at least as far back as 1980, without any clear evidence for the downstream propagation suggested by hypothesis 2. On the basis of the grain-size data alone, we cannot rule out the possibility that the entire upper river may have coarsened by 1978, when the first samples were collected. Indications from sediment transport modeling are also inconclusive about this. On the one hand, TUGS model predicts substantial dam-related increases in grain size as far downstream as RM 291 by the end of the simulations. This implies that coarsening probably migrated significantly further downstream—perhaps as far as Cottonwood Creek, or even beyond. On the other hand, we were unable to model this because we could not effectively quantify the timing and volume of in-stream mining and tributary inputs below RM 290. Taken together, these data and observations are inconclusive with regard to hypothesis 2.

For hypothesis 3 to be reasonable, there should be evidence indicating that bed-surface mobility has decreased significantly throughout the upper river, and that fine sediment concentrations in the subsurface of the channel bed have increased substantially over time. Our analysis of available data indicates that there has indeed been a significant decrease in mobility of the bed surface over time, due to dam-related coarsening and changes in the magnitude-frequency relationship of flow. On the other hand there is virtually no support for an increase in fine sediment concentrations in the bed. This is due, in large part, to a paucity of quantitative baseline data (i.e., from before 2005) on fine sediment concentrations and permeability. More quantitative conclusions about changes in fine sediment concentrations in the subsurface should be possible in future studies, with the help of the baseline permeability data presented here. Taken together, the balance of evidence does not support hypothesis 3. More conclusive tests will be needed in future studies.

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1 INTRODUCTION

The gravel resources of the Sacramento River have been the object of considerable study and management over the past two decades, in part because they are a fundamental building block of the river's aquatic and riparian habitat, with particular importance for salmonids. The Sacramento River currently supports several salmonids, including spawning populations of steelhead (*Oncorhynchus mykiss*) and four races of Chinook salmon (*O. tshawytscha*). The Sacramento River also supports the only self-sustaining population of winter run Chinook salmon, which is listed as an endangered species (Figure 1).

Though many factors influence salmonid population dynamics, the extent and quality of gravel deposits is often a critical factor because of their importance for successful spawning and rearing. The extent and quality of spawning gravel resources are regulated by the magnitude and frequency of flow and sediment transport, which have been substantially altered by human activity within the Sacramento River. Considering the importance of gravel to salmonids and other species, it is crucial to understand how the quality and extent of spawning gravel in the Sacramento River has changed.

This report presents the results of the Sacramento River gravel study, a component of the Sacramento River Ecological Flows Study administered by The Nature Conservancy (TNC) with funding from the California Bay-Delta Authority's Ecosystem Restoration Program (CALFED grant ERP-02D0P61). The Sacramento River Ecological Flows Study was designed to help identify how management of key elements of the river's natural conditions can help promote a healthy ecosystem while simultaneously providing for human needs. The gravel study is one of several efforts to address project goals by documenting how habitats in the riparian corridor have been affected by anthropogenic activity.

The gravel study in particular was designed to satisfy three general objectives defined in the Statement of Work for the Agreement between TNC and Stillwater Sciences:

Objective 1. refine estimates of the flow required to mobilize and scour sediment from the bed (Subtask 2.1),
Objective 2. characterize gravel and its habitat value for salmonids (Subtask 2.3), and
Objective 3. provide data for application of The Unified Gravel-Sand (TUGS) model (Subtask 3.1), a new sediment transport model that can predict the evolution of grain-size distributions in the surface and subsurface of a channel bed.

The gravel study included sampling approaches that built on results of previous work, including surveys of spawning habitat area (CDWR 1980) and studies of gravel quality and distribution (CDWR 1980, Buer 1984, CDWR 1995). Previous grain-size data were used as a baseline for comparison with new field data to help identify trends in grain-size distributions of the bed. When combined with initial motion modeling of bed sediment, the time series of grain-size data not only sheds light on thresholds for mobilization and scour of sediment (Objective 1), but also helps quantify how they have changed over time. CDFG and CDWR maps of spawning area in the Sacramento River from 1964 and 1980 were digitized to support a detailed, GIS-based analysis of changes in spawning gravel over time. Results from the previous habitat surveys were then used as a baseline for comparison with results from a new survey conducted in 2005. When considered together with new and existing grain-size data, the time-series of habitat surveys helps characterize gravel and its habitat value for salmonids (Objective 2), and helps document how spawning gravel has changed over time. Finally, the grain-size data from the gravel study was also used as input for TUGS sediment transport modeling (Objective 3), for both current conditions and historical conditions documented by previous studies.

By summarizing the findings of the gravel study and explaining the relevance of the results to resource management, this report should improve understanding of how changes in the frequency and magnitude of flow releases have affected spawning gravel in the Sacramento River. The new data and analyses from this and other components of the Sacramento River Ecological Flows project will be important inputs for the Sacramento River Ecological Flows Tool (Sac EFT)—a computer database for evaluating ecological trade-offs associated with potential management actions, including changes in flow regulation and bank protection.

The gravel study design was influenced by several working hypotheses about how spawning gravel has changed over time. Before discussing the study and its results, we first describe the study area and provide a synopsis of our working hypotheses.

1.1 Study Area

The Sacramento River drains over 15% of California, making it the state's largest and arguably most important river. Its headwaters include mountain slopes of the northern Sierra Nevada, the southern Cascades, and the southeastern Klamath Mountains. The gravel study area focused on the mainstem Sacramento River (Figure 2) below Keswick Dam (RM 302), which bars upstream passage of anadramous fish.

The Sacramento River below Keswick Dam (RM 302) is commonly subdivided into "upper", "middle", and "lower" sections, based on geomorphic process, form, and the effects of anthropogenic factors. The "upper" river, from Keswick Dam (RM 302) to Red Bluff (RM 243), has historically had a stable planform and profile, due to effects of geologic controls that prohibit extensive lateral migration (Brice 1977, CDWR 1980) or incision (CDWR 1980). Human-induced changes in the upper river are, therefore, most likely to be reflected in changes in the grain size distribution of the bed. In the "middle" river, from Red Bluff (RM 243) to Colusa (RM 143), both the planform and the bed surface have evolved noticeably over time (Brice 1977) due to relatively erodible deposits and a floodplain that is prone to periodic inundation. In the "lower" river, below Colusa (RM 143), lateral migration is restricted by levees, which have effectively severed the river from its floodplain.

Gravel deposits occur throughout the upper and middle sections of the river, forming a disconnected patchwork of spawning-sized material from Keswick Dam (RM 302) to Colusa (RM 143) (Figure 2). The downstream extent of salmonid spawning in the mainstem Sacramento River is near Princeton (RM 164), where fall-run Chinook salmon are able to spawn. The focus of this gravel study, therefore, extends from Keswick Dam (RM 302) to Princeton (RM 164), spanning the upper and middle sections of the river. Drainage area increases from 23,000 km^2 (8,900 m^2) at Red Bluff (RM 243) to 31,300 km^2 (12,100 m^2) at Colusa (RM 143).

1.2 Suitability Criteria of Spawning Gravel

To understand how anthropogenic changes have affected spawning gravel on the mainstem, it is necessary to consider the key characteristics of "suitable" salmonid spawning gravel. We identify three suitability criteria below.

1.2.1 The size and abundance of "immovable" particles

To protect their eggs against the potential for bed scour, spawning fish need to be able to move enough material to first excavate their redds deeply and then cover their egg pockets with sufficient material from upstream. These efforts can be frustrated if there is a locally high overall percentage of material that is too coarse for the fish to move. This suggests at least two upper limits on particle size:

1. the size of the largest movable particle, and
2. the maximum percent coverage of immovable material within hydraulically suitable riffles.

These limits are governed by (i) the size of the spawning fish and (ii) local hydraulic conditions including velocity and slope, which can alternatively improve or inhibit a fish's ability to move a particle of a given size. Because local hydraulic conditions vary substantially from point to point on river beds, it is difficult to quantify the size and abundance limits on immovable particles for spawning fish of a given size. However, there is some indication, based on direct field observations from the nearby Feather River, that Chinook salmon are not able to successfully spawn in deposits where more than 40% of the surface is covered by particles with intermediate axis lengths bigger than 130 mm (Stillwater Sciences unpublished). Though the overall scale of the Sacramento and Feather rivers are dramatically different, salmonid spawning habitat preferences are similar enough at the scale of individual riffles, so we have adopted the working hypothesis that the two systems produce similar upper limits on particle size for suitable spawning gravel. We were able to investigate this hypothesis using data from the Sacramento River collected as part of this gravel study, which is discussed in greater detail later in this report.

1.2.2 Limit on the percentage of fine material

The suitability of gravel for spawning salmonids is also governed by the percentage of fine sediment (e.g., <2 mm) (McCuddin 1977, Reiser and White 1988). Although there is some indication that spawning success may be low in manually added gravel if fine material is not present (Carl Mesick Consultants 2002), there are important implications for the survival of salmonid eggs and alevins in spawning redds as the concentration of fine sediment in the subsurface increases. Salmonid survival from egg incubation through fry emergence requires adequate delivery of dissolved oxygen and removal of metabolic wastes via intragravel flow (Figure 3). When fine sediment becomes heavily concentrated in (or on) a streambed, the rate of intragravel flow in the substrate can be substantially reduced, thus depleting dissolved oxygen concentrations and increasing metabolic waste around incubating eggs, larvae, and sac-fry as they develop within egg pockets (Kondolf 2000). This can lead to high mortality. Abundant fine sediment around egg pockets can further increase mortality of salmonid fry via entombment, with fine sediment plugging interstices so that fry cannot emerge.

Spawning-sized gravel is mobilized in the spawning reaches of the Sacramento River by floods that have low frequency and high magnitude (e.g., greater than about 50,000 cfs in the vicinity of Redding; CDWR 1980). Finer material (including sand, silt, and clay) can be mobilized by the river's more frequent, lower magnitude flows. When mobilized, grains of sand tend to saltate (i.e., hop) along the bed and can eventually infiltrate the interstices between the coarse particles that form the framework of the channel bed. In the absence of periodic flushing flows (that are large enough to scour the subsurface), fine sediment can become concentrated in the channel bed and reduce spawning habitat quality.

Fine sediment can also be cleaned from the subsurface by adult salmon during redd construction, which disrupts the surface and entrains sand and finer material into the downstream water flow (Kondolf 2000). However, if flow is locally slow, sand may not be entrained very effectively during redd construction. If this is the case, then female salmon may inadvertently contaminate their redds with fines as they cover their eggs with sediment from upstream of the egg pocket.

1.3 Factors Affecting the Extent and Quality of Spawning Habitat

Resource use in the Sacramento River Valley over the past 150 years has been a crucial component of California's economic growth. Ecological consequences have been substantial, as aquatic, floodplain, and riparian habitats have been destroyed or degraded and populations of many native species have plummeted. In the subsections that follow, we highlight the key human-induced changes that have affected the extent and quality of spawning gravel for steelhead and Chinook salmon in the mainstem Sacramento River.

1.3.1 Fish-passage barriers

The history of fish-passage barriers on the Sacramento River extends back to the mid-19th century, when upstream migration of salmonids was inhibited by mining diversions near the Pit River confluence with the Sacramento River (CFC 1890). Spawning habitat continued to be available downstream of the Pit River and in other tributaries (e.g., McCloud and Little Sacramento rivers) until 1917, when seasonal operations of the Anderson Cottonwood Irrigation District (ACID) Dam (RM 298.3) began disrupting salmonid access to historical spawning habitat. Similarly, the Red Bluff Diversion Dam (RM 243.5) began disrupting upstream passage in 1964.

Excavations at Shasta Dam site (RM 312) began in 1938 and led to permanent blockage of upstream-migrating fish beginning in 1940. By 1942, construction at Keswick Dam had further restricted anadromy to reaches downstream of RM 302 (Figure 4). Overall, the major dams of the upper Sacramento River (e.g., Shasta and Keswick dams on the mainstem, and Whiskeytown Dam on Clear Creek) have permanently blocked access to an estimated 80% or more of the watershed's historical salmonid spawning habitat (Lindley et al. 2006; compare Figure 1 and Figure 4).

1.3.2 Effects of dam-related changes in flow

The construction of Shasta and Keswick dams inaugurated an era of flow regulation in the Sacramento River that has dramatically altered the magnitude and frequency of water discharge (Pike 2002). From an ecological perspective, the most important dam-related changes in the flow regime probably include (i) reductions in the frequency and magnitude of high flows, (ii) increases in summer base flow, and (iii) reductions in the day-to-day and year-to-year variability of flow (Kondolf et al. 2000). Given that sediment transport is strongly regulated by flow, with only relatively large, infrequent floods providing enough energy to mobilize coarse sediment in most rivers, the effects of dam-related changes in flow have altered sediment transport in the Sacramento River. For example, the change in the magnitude of the 1.5-year flood ($Q_{1.5}$) has been reduced by nearly 30% at Keswick Dam, from a pre-dam magnitude of from 86,000 cfs (2,400 m^3/s) to 61,000 cfs (1,700 m^3/s) (Kondolf et al. 2000). In rivers of the western United States, the $Q_{1.5}$ flow is often correlated with the "bankfull" flow in unregulated rivers (Leopold et al. 1964), making it a reasonable first approximation for the "dominant" discharge—the discharge responsible for conveying the greatest fraction of the river's load (Wolman and Miller 1960).

This suggests that the recurrence interval of the bankfull (and, presumably, dominant) discharge has increased substantially in reach near Keswick Dam. Such regulation-induced changes in the frequency-magnitude relationship of flow have likely reduced the frequency and magnitude of coarse sediment transport in the mainstem below Keswick Dam.

1.3.3 Dam-related effects on sediment supply

In addition to the effects of Keswick and Shasta dams on fish migration and discharge in the mainstem Sacramento River, the dams have also altered the sediment supply rate, which is the other main regulator of sediment transport in the river. Sediment supply from the upper watershed has been trapped since 1940, when temporary cofferdams were constructed to divert water around the Shasta Dam construction site. The estimated average natural rate of coarse sediment supply from the upper watershed, in the vicinity of Keswick Dam, is approximately 46,000 m^3/yr (60,000 yd^3/yr) (CDWR 1980), implying a cumulative deficit in supply of approximately 3 million m^3 (4 million yd^3) over the six decades since dam construction began. This overall reduction in coarse sediment supply in the upper river was exacerbated by more than 5.4 million m^3 (7 million yd^3) of in-stream mining of gravel and sand to support dam construction. Other dam-related modifications that have affected gravel quality for salmonids—including changes in water temperatures and LWD loading—are not directly relevant to the gravel study, which focused on assessing grain size and how it affects the extent and quality of spawning gravel.

1.3.4 Aggregate mining

Dam-related mining of sediment from the upper Sacramento River and its tributaries was first attended by and later replaced by aggregate extraction for regional urbanization and interstate highway construction (CDWR 1980). For example, 0.75 to 1.15 million m^3 (1.0 to 1.5 million yd^3) of locally mined aggregate was used to help build Interstate 5 between Red Bluff and Corning in the 1960s (Buer 1984). Aggregate mining on Sacramento River tributaries continues to support urban needs (CDWR 1980, Buer 1984, Buer 1994), accounting for removal of roughly 1.4 million m^3 (1.8 million yds^3) of gravel and sand per year from creeks and rivers of Shasta and Tehama counties.

Extraction via in-stream aggregate mining in the mainstem has reduced the amount of sediment stored in the bed. With the dams blocking sediment delivery from upstream, tributaries like Stillwater Creek, Cow Creek, and Cottonwood Creek are the last of the upper river's natural sources of coarse sediment. As a consequence, mining in tributaries and from floodplains has compounded the system-wide reduction in sediment supply that can be attributed to Shasta and Keswick dams. Remnant mining pits on the mainstem (e.g., Kutras Park and Turtle Bay) have the additional effect of trapping sediment in transit from upstream. This has presumably disrupted the continuity of sediment transport, so that effects of gravel augmentation implemented upstream of the sediment traps) are unlikely to have translated downstream to offset the loss of sediment supply. The effects of aggregate mining have contributed to a substantial overall decrease in the rate of sediment supply and transport in the upper river.

1.4 Hypotheses about Changes in Gravel Quantity and Quality

Consideration of how the processes outlined above are likely to have affected the Sacramento River system led us to develop three hypotheses about how the extent and quality of spawning gravel have been changing over time (Stillwater Sciences 2005; Appendix C):

Hypothesis 1. The quantity of spawning gravel has been decreasing over time due to bed-surface coarsening associated with the effects of in-stream mining and dam-related reductions in sediment supply from headwater sources (Figure 5).

Hypothesis 2. Bed-surface coarsening has propagated progressively downstream from the dams (Figure 6).

Hypothesis 3. The quality of any remaining spawning gravel in the upper river has declined in concert with the river's ability to flush fine sediment from the subsurface of its bed, due to reduced surface mobility —a consequence of (i) coarsening and (ii) the reduced frequency and magnitude of peak winter floods.

In the gravel study, we explored these hypotheses by quantifying trends in grain-size distributions, bed elevations, gravel permeability, and area used by spawning fish. Data sources included (i) results from a new sediment transport model (ii) historical results from previous studies, and (iii) observations and measurements from a new field study. In the next section we describe our methods for measuring grain size, permeability, bed scour, and spawning area. We also discuss how trends were estimated from the various data sets and present results from the sediment transport analyses. We then assess our working hypotheses, and revise, as needed, our conceptual model for how spawning gravel has changed over time. We conclude by discussing implications for management of salmonid populations of the Sacramento River.

2 METHODS

The types of measurements and analysis performed in the gravel study include habitat surveys; measurements of grain size, gravel quality, and scour; and modeling of sediment transport under conditions consistent with those in the Sacramento River since Shasta and Keswick dams were constructed. A complete list of sampling locations and the types of measurements and analysis that were performed at each site or reach is provided in Table 1.

Table 1. Location of samples and types of measurements in the 2005–2006 gravel study.

ID	RM	Habitat area	Grain size§	Permeability	Scour†	TUGS model
"Upper River"	302–273	mapped in 1948, 1964, and 1980 reanalyzed in 2005 remapped in 2005				
"Reach 1"	302–299.5					analyzed in 2005
"Reach 2"	299.5–295					analyzed in 2005
F6	298.8		F			
SWW-1	298.3		W			
SWW-2	297.2		W			
SWW-3	296.15		W			
"Reach 3"	295–289.5					analyzed in 2005
SWW-4	294.84		W			
SWW-5	294.33		W			
SWW-6	293.02		W			
SWW-7	293.0		W			
F4	292.7		F			
SWW-8	292.5		W			
SWW-9	291.5		W			
F3	291.4		F			
SWW-10	291.2		W			
F2	290.8		F			
SWW-11	289.2		W			
SWW-12	288.0		W			
F1	287.7		F			
SWW-13	286.3		W			
SWW-14	282.6		W			
SWW-15	281.8		W			
SWW-16	280.1		W			
SWW-17	279.1		W			
SW-7	278.5		B, W	√		
SW-8	275.8		B, W	√		
SW-10	273.0		W		SC, SB	
SW-6	271.8		B, W	√	SB	
SW-11	246.2				SC	
"Middle River"	243–143	mapped in 1964 and 1983				
SW-2	239.4		B, W	√	SC, SB	
SW-3	236.8		B, W	√	SC, SB	
SW-4	234.2		B, W	√		
SW-1	228.2		B, W	√	SC, SB	
SW-5	211.0		B, W	√		
SW-9	163.2		B, W	√		

§ "B" stands for bulk sampling, "W" stands for Wolman bed surface pebble count, and "F" stands for facies mapping
√ indicates multiple permeability measurements were made at the site
† "SC" stands for scour chain and "SB" stands for scour box

2.1 Measurement of Spawning Area

As one test of hypothesis 1—that the quantity of spawning gravel has been decreasing over time due to coarsening—we estimated the extent of usable spawning area at a several points in time to determine whether any changes have occurred. In streams and rivers where numbers of returning adult salmonids are sufficient to "saturate" usable spawning area with redds, measurements of the spawning area provide measurable indicators of the extent and distribution of usable gravel. Any changes in spawning area from one year to the next on such a river would generally indicate spawning habitat losses (as postulated for the Sacramento River as a whole in hypothesis 1) or gains (as may be the case locally, near gravel augmentation sites or tributaries). Observations from our facies mapping efforts indicate that fall run Chinook salmon were actively spawning wherever suitable bed material and hydraulics converged, even in small deposits which are marginally suitable (see section 3.2.3 for further discussion). This implies that returns of fall-run Chinook salmon on the Sacramento River were abundant enough in 2006 to saturate the usable spawning area. It further suggests that aerial redd surveys conducted during the fall-run spawning peak may often provide useful, though not perfect, indicators of usable spawning habitat in the Sacramento River mainstem. This assumption is evaluated in greater detail for each of the spawning surveys in section 3.1.

2.1.1 Analysis of historical spawning area distributions

Results from aerial redd surveys conducted in 1964, 1980, and 1983 during the fall-run spawning season were presented by CDWR (1980 and 1984), along with spawning areas mapped in March 1948, in spawning gravel atlases (CDWR 1980 and 1984). One sheet of the 1980 atlas is reproduced as Figure 7 for illustration. An initial, qualitative assessment of the redd distributions by CDWR (1980) revealed that the extent of spawning area in 1980 was noticeably reduced relative to what it had been in 1964, particularly in the reaches upstream of Anderson Bridge, at RM 283.3 (CDWR 1980). CDWR argued that this observation supported the hypothesis that the bed had coarsened in the interim, at least in the uppermost spawning reaches of the Sacramento River (CDWR 1980).

As part of this gravel study, the analyses of spawning maps from 1948, 1964, 1980 and 1983 were re-analyzed to obtain a more refined, quantitative estimate of habitat loss for individual reaches of the upper and middle sections of the river. As a first step, the mapped boundaries of spawning patches were digitized into a GIS database. Areas of patches were grouped into bins spanning 1 river-mile each and compared with data from preceding years for estimation of localized changes over time.

The mile-long groupings of habitat area permits improved resolution of losses in the intervening period. It also permits a more detailed assessment of factors influencing local changes in habitat area. In particular, the effects of tributaries and gravel injection projects should be more clearly evident than they were in the qualitative assessments of CDWR (1980). In addition, the precise locations of remnant mining pits and deep pools have now been assessed so that their sediment-trapping effects can be better quantified and understood. In this way, the revised spatial analysis of spawning area has helped point to mechanisms underlying observed changes in spawning habitat and the grain-size distributions of channel bed materials.

The time series of spawning habitat surveys provides a useful tool for assessing changes in gravel resources that influence the distribution of salmonid spawning. However, researches have noted that aerial redd surveys can often misidentify the location and number of redds (D. Killam, personal communication, December 14, 2006). Water clarity and visibility can obscure redds from view, thus interfering with accurate habitat mapping and leading to an under-representation of redds. Conversely, mapping from the air can also over-represent the abundance of redds when areas of high contrast are mistakenly mapped as redds. This makes field checking an important component of aerial habitat surveys. Though these factors complicate the use of aerial redd surveys as a tool for assessing changes in salmonid spawning habitat, they do not negate the value of the redd surveys for this purpose, especially in terms of a broad evaluation of trends in the distribution and extent of spawning gravels.

2.1.2 Collection and processing of spawning area data from 2005

Since the habitat surveys of 1980, the river has conveyed numerous flows big enough to mobilize gravel from the channel bed. We hypothesize that these high flow events winnowed spawning gravel in the upper river and contributing to additional bed coarsening and a concomitant decline in spawning habitat area. To assess this hypothesis, we conducted an aerial survey of spawning area in 2005 using methods similar to those used for the 1964 and 1980 habitat surveys.

For the 2005 survey, we recorded aerial images of the channel on video camera for the reach between Keswick Dam (RM 302) and Red Bluff (RM 243). This was accomplished by mounting a broadcast-quality video camera to the nose of a helicopter. The camera output was sent to a digital video recorder, where the image was stamped with the location of the helicopter, which was updated continuously using a GPS unit. The camera was controlled remotely during the helicopter flight to ensure that the full width of the channel was captured on video. For reaches with multiple channels, each channel was mapped separately to maintain visual resolution to assist the process of redd identification.

Because the video images can be magnified and examined frame by frame, the video-based methods of the 2005 survey are capable of producing a much finer resolution of spawning habitat area than was possible by the methods used in 1964 and 1980. The video record also allows more careful study of potential redd locations than the real-time mapping used during the 1964 and 1980 surveys. Despite these differences in methods, we can retain consistency among the data sets by grouping mapped polygons by river mile for each time step, so that results from the different surveys are roughly comparable.

We conducted the aerial survey on November 22 and 23, 2005, when fall-run Chinook salmon were spawning in the mainstem Sacramento River. We focused the survey on fall-run spawning because their escapements are highest among the salmonids that spawn in the mainstem. This makes them most likely to "saturate" the available spawning area, and thus helps provide the best opportunity to estimate total available spawning habitat area in the mainstem. The spawning habitat survey focused on the reach between Keswick Dam (RM 302) and Red Bluff Diversion Dam (RM 243.5).

After maps were generated from close inspection of the video footage, redds were digitized in GIS for analysis of spawning habitat area and for comparison with the 1948, 1964, and 1980 survey data. Decreases and increases in mapped spawning in individual reaches were determined and assessed within the context of the bed-coarsening hypothesis and also with results from other facets of the gravel study.

2.2 Measurement of Grain-size Distributions

We characterized grain-size distributions of the channel bed across a range of scales. At select riffles, grain-size distributions of the surface and subsurface, provided a quantitative, localized picture of bed-material size for comparison with measurements taken by CDWR in the 1980s and 1990s. For a broader, reach-scale picture of how average grain size varies on the bed, we constructed maps of surface sediment size distributions (i.e., facies) for select sites in the upper river, based on visual assessment in the field. To our knowledge the facies maps are the first of their kind for the upper mainstem of the Sacramento River. Consequently, they provide a baseline for monitoring changes over time, in addition to giving a broad general picture of how grain size varies with distance downstream.

2.2.1 Bulk sampling of the surface and subsurface

By determining grain-size distributions of the surface and subsurface, bulk sampling provides a means to quantify the degree of "armoring" by relatively coarse surface sediment. Bulk sampling of the bed was conducted in October 2005 at 9 locations corresponding to historical grain-size sampling sites of CDWR (CDWR 1980, Buer 1984, CDWR 1995), as listed in Table 2. At each site, we attempted to reoccupy the same "geomorphic position"[1] that was sampled in the previous studies, so that the grain-size data from the different sampling efforts would be comparable.

Table 2. Names and locations of bulk samples on riffles in the 2005 study.

Site	RM	CDWR analog*
SW-7	278.5	BSBG-11
SW-8	275.8	BSBG-18
SW-6	271.8	–
SW-2	239.4	BS-4
SW-3	236.8	BS-9
SW-4	234.2	BS-10
SW-1	228.2	BS-8
SW-5	211	BS-12
SW-9	163.2	BS-2

* Samples labeled with "BSBG" prefix are from CDWR's upper river gravel study (CDWR 1995), whereas samples labeled with "BS" prefix are from the middle river gravel study (Buer 1984).

A short section of a 1-m (3-ft) diameter culvert was worked vertically into the bed at each sample point to act as a flow curtain (Figure 8), stilling the flow locally and thus minimizing the washing of fines from the samples. Samples were collected by hand from the surface and subsurface separately. A grain scoop (i.e., of the kind typically used for livestock feed) was used for collecting gravel and finer material. Surface depth was defined as the depth equivalent to the b-axis length of the largest surface particle (e.g., Church et al. 1987). The samples were weighed in

[1] By "geomorphic position" we mean a location on the bed having a particular geometry and array of flow depths and velocities (and thus shear stresses) across the hydrograph in a given year. CDWR sampled the heads of riffles in 1980 and 1995, so we group them here as a single "geomorphic position" for the purposes of comparing grain sizes, both from site to site and from sampling interval to sampling interval.

buckets using a spring scale after being wet-sieved on the nearest flat bank surface using a set of standard sieves (i.e., 76.2 mm [3 in], 38.1 mm [1.5 in], 19.1 mm [0.75 in], 9.5 mm [0.375 in], and #4). Particles with intermediate-axis diameters exceeding 152 mm (6 inches) were sorted by hand with a ruler and weighed individually. Sand and finer material (i.e., whatever passed the #4 sieve) was sub-sampled and packaged for later laboratory analysis by dry sieving through finer sieve sizes (i.e., #8, #16, #30, #50, #100, and #200). The mass of collected material was adjusted at each site to conform to accepted standards for statistical analyses of grain size distributions (Church et al. 1987), in which minimum sample mass varies with the length of the largest particle in the sample layer. In this case, sample masses ranged from 127 to 336 kg, depending on surface grain size.

2.2.2 Wolman pebble counting

To further document how grain-size distributions of the bed change as a function of distance downstream, Wolman pebble counts (Wolman 1954, Leopold 1970) were conducted at 27 locations corresponding to historical grain-size sampling sites of CDWR (CDWR 1980, Buer 1984, CDWR 1995), as listed in Table 3. In a Wolman count, the intermediate (or "b") axes of 100 bed surface particles are measured. Wolman counts are quicker than bulk sampling, but do not reveal information about the subsurface. Even so, from the distribution of b-axis diameters determined by Wolman counts, it is possible to identify grain-size indexes including the median particle size (D_{50}), the geometric mean of particle sizes (D_g), and the D_{84} and D_{16} (i.e., the diameters that correspond to 84% finer and 16% finer in cumulative distribution functions of grain size). By conducting Wolman counts at sites that are geomorphically similar to sites of Wolman counts in previous CDWR studies (i.e., at the heads of riffles—see footnote 3), we were able to document changes in grain-size distributions over time and assess their statistical significance.

Table 3. Names and locations of Wolman pebble counts at riffles of the Sacramento River.

2005 Gravel Study		Historical Analogs from CDWR Studies					
		1980/1984*		1995†		2001§	
Site	RM	Site	RM	Site	RM	Site	RM
SWW-1	298.3	SR-4	298.3	SBG-8	298.3		
SWW-2	297.2	SR-5	296.95	SBG-10	297.1		
SWW-3	296.15	SR-93	296.15				
SWW-4	294.84	SR-11A	294.84				
SWW-5	294.33	SR-12	294.33				
SWW-6 SWW-7	293.0 293.0	SR-13	293.02				
SWW-8	292.5	SR-16	292.6	SBG-9	292.5		
SWW-9	291.5			SBG-5	291.5		
SWW-10	291.2	SR-19	291.22	SBG-3	291.0		
SWW-11	289.2	SR-29 SR-24	289.16 289.16	SBG-7	289.0		
SWW-12	288.0	SR-31 SR-33	288 287.29	SBG-6 SBG-2	288.0 287.3		
SWW-13	286.3	SR-35	286.29	SBG-1	286.3		
SWW-14	282.6	SR-80	282.55	SBG-14 SBG-13	282.6 282.5		
SWW-15	281.8	SR-84 SR-85	281.78 281.7	SBG-12	281.8	CCFJ-6	282.0
SWW-16	280.1	SR-63	280.16	SBG-15	280.1	CCJF-8	280.1
SWW-17	279.1	SR-59	279.1	SBG-16	279.1	CCJF-9	279.2
SW-7	278.5	SR-53 SR-54 SR-55	278.29 278.29 278.27	SBG-11	278.5	CCJF-10	278.7
SW-8	275.8	SR-89	275.68	SBG-18	275.7	CCJF-11	275.8
SW-10	273.5	SR-103 SR-105 SR-106	273.25 273.4 273.5	SBG-17 SBG-20	273.5 273.1	CCJF-4	273.5
SW-6	271.8	SR-107	271.75			CCJF-5	271.8
SW-2	239.4	WMS-6 WMS-7 WMS-8	240.4 240.1 239.8				
SW-3	236.8	WMS-12	236.1				
SW-4	234.2	WMS-14 WMS-15	234.8 234				
SW-1	228.2	WMS-19	228.3				
SW-5	211.0	WMS-28	211.3				
SW-9	163.2	WMS-54	163.5				

* Samples labeled with "SR" prefix are from CDWR's upper river gravel study (CDWR 1980), whereas samples labeled with "WMS" prefix are from the middle river gravel study (Buer 1984).
† Source CDWR (1995).
§ Source CDWR (2002).

2.2.3 Facies mapping

We conducted the facies mapping field work in December 2006 at five locations between RM 299 and RM 287 (Table 4), using 2005 National Agriculture Imagery Program (NAIP) aerial photos of the mainstem Sacramento River as base maps. Site selection was guided by analysis of

CDWR's (1980) historical spawning area maps (from 1948, 1964, and 1980) and the aerial video footage from the 2005 spawning area survey. We wanted the facies mapping study to inform an analysis of the mechanisms of changes in spawning habitat area over time. To optimize our experimental design, we focused on sites where significant changes in local spawning area were suggested by the time-series of spawning habitat.

Table 4. Locations and characteristics of facies mapping sites on the Sacramento River.

ID	RM	Number of polygons	Total area (ha)	Number of pebble counts	Spawning in 1948*	Spawning in 1964*	Spawning 1980*	Spawning in 2005†
F-1	287.7	12	6.8	2	extensive areas around island	few changes evident	changes consistent with island growth	changes consistent with island growth
F-2	290.8	8	8.8	3	none present	two new areas appear	just one small area in new position along left bank	spawning along bank reduced and shifted upstream
F-3	291.4	11	5.8	3	extensive area on right margin of left branch	area on right margin gone; new area at head of island	new areas appear along margins	loss of new areas from 1980
F-4	292.7	7	3.7	2	extensive area on left margin	area reduced	minimally changed	area is much reduced
F-6	298.8	8	8.0	2	extensive, channel-spanning area	area essentially unchanged	area substantially reduced	present only along banks

*based on spawning area maps of CDWR (1980)
†based on field observations and spawning area video captured in this study (see also section 3).

The goal of sedimentary facies mapping is to delineate the surface into distinct units, or polygons, by size class (Buffington and Montgomery 1999). Robust, repeatable results can generally be obtained in short (e.g., 20–50-m long) reaches. To be applicable to the large study reaches of the Sacramento River, the facies mapping methodology was modified to capture a relatively coarse-scale classification of sedimentary facies (Stillwater Sciences 2004).

Classification is based on field estimates of the proportional occurrence of sand/silt [S], gravel [G], cobble [C], boulder [B], and bedrock [br]. Lack of precision in the field estimates generally limits the resolution of the estimated proportional occurrences to increments of 5%. A substrate type (i.e., sand, gravel, cobble, boulder, or bedrock) qualifies for classification if it covers ≥5% of the surface. The surface is classified in reverse order of the proportional occurrence of qualifying substrate types, with the dominant one being listed last with a capital letter. For example, if cobble covers more than 95% of the surface, the facies is classified simply as "cobble" [C]. For a mostly cobble-covered surface that is accompanied by 5% or more of "subordinate" gravel, the facies is classified as a "gravelly cobble" [gC]. If another substrate type, such as boulder, also covers 5% or more of the surface, the facies is classified with two subordinate classes, as "bouldery gravelly cobble" [bgC], for example, when the gravel covers more area than the boulders, or "gravelly bouldery cobble" [gbC], when the boulders cover more area than the gravel. In addition to assessing the proportional occurrence of qualifying substrate types, we also visually estimated mean particle size and the total percent of the surface covered by particles with intermediate axis diameters >130 mm for each of the facies. All measurements were performed by a single team of two technicians to reduce the potential for variability introduced by individual mapping biases.

Because facies mapping relies heavily on visual inspection of the bed, it provides a somewhat subjective assessment of the distribution of substrate types and sizes. This is particularly true for large rivers, such as the Sacramento River, where visual inspection of some of the bed may be difficult or impossible due to deep, swift water. To help calibrate the facies maps and make them less subjective, we conducted Wolman pebble counts periodically throughout the exercise in shallow riffle areas, where we could safely access the bed. Although our control points for grain size were restricted to safely accessible riffles, the boundaries of the facies maps themselves generally encompassed the entire river, including deeper areas were the bed was visible from a boat but unsafe for wading. We used the distribution of measured b-axis diameters from the Wolman counts to identify the percent of area covered for each the dominant facies, based on standard cutoffs for grain-size classification (i.e., > 256 mm = boulder, > 64 mm = cobble, > 2 mm = gravel, <2 mm = sand/silt). At each calibration site, we compared the calculated percentages from the Wolman counts with the visual assessment of the facies unit, to determine uncertainties and to assess whether we needed to revise the mapped designations. We conducted two to three Wolman counts in tandem with the facies mapping exercise in each of the study reaches. We also photographed the surface at each site using a camera oriented perpendicular to the bed. We used an underwater camera to calibrate the mapping in deep water. With the help of a graduated scale (with 50-mm increments), which was placed on the bed at each photo site, we used the photographs as an additional, quantitative check on the reliability of the facies maps. The pebble count data for each location were compiled into particle size distributions and entered into an Arc-GIS database, along with polygon boundaries and other field data from the facies maps.

In addition to mapping the distribution of bed sediment sizes, we identified whether hydraulic conditions (e.g., flow depths and velocities) were roughly suitable for spawning within each facies. We also delineated the distribution of redds and spawning salmon during the facies mapping exercise. By quantifying spawning use, together with hydraulic suitability and grain size, our facies mapping work provides the means to quantify the upper limits on grain size for spawning Chinook salmon, as discussed in greater detail in section 3.2.3.

The 2006 facies maps provide an important baseline for comparison with future conditions, which can be mapped in successive years after geomorphically significant flows to track any changes over time. As elaborated later, we used results from the facies mapping, in conjunction with historical results from spawning habitat surveys (from 1948, 1964, and 1980), as a basis for explaining local losses and gains in spawning area from 1980 to 2006.

2.3 Measurement of Permeability

Permeability measurements determine the rate of intragravel flow (in volume per unit time) using a suction device operated at a known pressure. They provide a cost-effective means of assessing spawning gravel quality. In the Sacramento River gravel study, permeability was measured using a modified Terhune (1958) Mark VI stainless steel permeability standpipe driven into the river bed (Barnard and McBain 1994):

1. Using a sledgehammer and driving cap (to protect the top of the permeability standpipe), pound the permeability standpipe into the bed to a depth of 15 cm (6 in) (Figure 9).
2. Remove the driving cap and place the sipping tube (Figure 9) from the permeability backpack into the standpipe. The sipping tube should be fitted with two collars: an upper, locking collar, to hold the sipping tube in place, and a lower spacer collar (measuring 2.54 cm, or 1 in, long). Adjust the height of the sipping tube so that its tip is precisely located at the water surface—identifiable by the first instance of audible sucking as the tip is lowered toward the water.
3. Remove the spacer collar, so that the sipper is 2.54 cm (1 in) below the water surface.
4. Activate the vacuum pump on the permeability backpack, and simultaneously activate a stopwatch to record time.
5. When the cylinder on the permeability backpack (Figure 9) is filled with water to a defined height on the pack's graduated cylinder, turn off the pump and stop the timer. Record time on a data sheet.
6. Repeat steps 4 and 5 three to four times, to document inter-sample variability
7. Drive the pipe deeper, to 30 cm (12 in), to sample typical incubation depths of spawning salmonids (Chapman 1988, Bjornn and Reiser 1991) and repeat steps 2–6 for the new depth.
8. If possible drive the pipe to 45 cm (18 in) to sample depths that might be relevant for spawning gravel quality of the largest of the Chinook salmon of the Sacramento River and repeat steps 2–6 for the new depth.
9. Remove the standpipe and proceed to the next site.

Gravel permeability can vary significantly from site to site within a riffle. It was therefore necessary to measure permeability at multiple sites, to characterize the average permeability of each riffle (Table 5). Steps 1 through 9 were repeated at each site within the riffle. Sites were selected randomly within areas that were safe for wading. Overall, we measured permeability a total of 420 times at 31 sites within 9 riffles of the upper and middle Sacramento River.

Table 5. Names, locations, and number of permeability sites on riffles, 2005–2006.

ID	RM	Number of sites 2005	Number of sites 2006	Total
SW-7	278.5	5	–	5
SW-8	275.8	2	–	2
SW-10	273.0	–	–	–
SW-6	271.8	3*	2	5
SW-11	246.2	–	–	–
SW-2	239.4	4*	2	6
SW-3	236.8	2	–	2
SW-4	234.2	3	–	3
SW-1	228.2	1	2	3
SW-5	211.0	2	–	2
SW-9	163.2	3	–	3
total		25	6	31

*Permeability was measured at a 14-inch drive depth only at one of the sites using a relatively thick standpipe.

As female salmon build their redds, the concentration of fine sediment in the spawning gravel is usually reduced due to disturbance of the bed in the presence of flowing water (which carries away the fines). This generally leads to an increase in permeability in newly constructed redds, relative to undisturbed conditions in the bed. We therefore expect that permeability measured by steps 1 through 9 above may not yield results that are fully representative of permeability in gravel around incubating eggs. To help quantify how permeability changes when adult salmon mobilize coarse material during redd construction, we measured permeability (using steps 1 through 9 outlined above) both before and after attempting to simulate redd building at select sites. To simulate redd building, we used a McCloud rake to first dig to a depth of roughly 30 cm (12 in) beneath the surface of the bed, and then cover the excavated pit with material from immediately upstream.

2.4 Measurement of Mobilization Thresholds and Bed Scour

We used scour chains to help quantify depths of scour and deposition, and scour boxes to help quantify thresholds of mobilization. The names and locations of mobilization and scour sites are provided in Table 6 along with the number of chains and boxes that were installed at each site.

Table 6. Names, locations, and sample sizes of scour chain and scour box sites.*

Site	RM	Number of scour chains	Number of scour boxes
SW-10	273.0	3	3
SW-6	271.8	0	3
SW-11	246.2	4	0
SW-2	239.4	4	3
SW-3	236.8	4	3
SW-1	228.2	4	3

*daily average discharges during installation ranged between 5,060 and 5,070 cfs at Keswick Dam (RM 302) and between 6,430 and 6,470 cfs at the Red Bluff gauge (RM 258).

2.4.1 Scour chains

To quantify depths of scour and subsequent deposition during sediment transport events, a network of scour chains was installed and monitored during 2005 and 2006. Differences in local hydraulics associated with channel bedforms are expected to be the most important regulators of scour and deposition at the scale of individual riffles. Scour is expected to be most evident where flow velocities are relatively swift, at the upstream ends of submerged bars and riffles, whereas deposition is expected to be relatively common downstream of riffles. In order to sample hydraulic conditions typically associated with redd scour, a nest of chains was positioned at the upstream ends of riffle heads at each of the sites.

Scour chains were constructed from 1 meter-long lengths of 4.75-millimeter (3/16-inch) link chain. Chains were welded or bolted to flared steel wedges, which serve as anchors after the chains are driven into the gravel (Figure 10a). Each chain was driven vertically into the bed by hammering down on a steel pipe, which fitted over the chain and onto the anchor, forcing it deeper and deeper into the gravel with each successive hammer blow (Figure 10b). To ensure that the installed chain ran vertically through the gravel, it was held taut during installation using a string that ran from the end of the chain through a pre-drilled hole near the top of the driving pipe. Each anchor was driven to a minimum depth of 0.3 m (1 ft) and securely anchored to the bed. Secure anchorage was checked by forcefully pulling on the trailing end of the chain that protrudes from the gravel. The length of each trailing end of chain was recorded (Figure 10c) and locations of exit points from the gravel were surveyed by installing resection points (so that chains could be found during the monitoring phase of the study).

Scour chain sites were reoccupied in the October, 2006, and inspected for signs of flow-related changes. If the current protruding chain length exceeded the length that protruded from the bed on the previous visit, then the difference was assumed to be equal to the local depth of scour (Figure 10d). Deposition was indicated if the chain was completely buried. Coordinates from GPS readings were used in concert with the resection survey and a magnetometer to precisely locate chains that were buried. Buried chains were carefully excavated to determine the length of the buried chain. By comparing the buried length with the original length it is possible to quantify depths of scour and deposition (Harrelson et al. 1994, Lisle and Eads 1991).

2.4.2 Scour boxes

Scour boxes were used as an additional, semi-quantitative means for estimating the magnitude of flow required to mobilize the surface of the channel bed. To create our scour boxes, we painted dry, sub-aerially exposed surfaces with bright marking paint during low flow (i.e., between 5,000 and 6,500 cfs) conditions, in December, 2005 (Figure 11). We conducted the scour box study in the reach downstream of Cottonwood Creek (RM 273.5); coarsening has made the bed above Cottonwood Creek relatively immobile, so disruption of scour boxes is more likely to occur below the confluence. Scour boxes were located on surfaces that were broadly representative of the surrounding bar surface. We painted three 1.5 m x 1.5 m (5' x 5') boxes at each site. Scour boxes were spaced 20 meters apart, starting at the head of the exposed point bar and working downstream along the water's edge, to sample intra-site variability. We placed three scour boxes each at five sites, for a total of fifteen boxes.

Scour box studies are an *in-situ* approach to tracing particle mobility; the surface of the bed does not need to be disturbed to identify movement. This differs from the tracer particle approach, which can lead to preferential transport of tracer rocks due to the destabilization of the bed that typically occurs when painted rocks are manually installed on the surface.

Disruption of scour boxes by high flows is an indication of bed mobilization, which can be correlated with discharge data from the nearest flow gauge to identify the range of flow magnitudes that were responsible for bed mobilization.

In the gravel study plan, we asserted that scour boxes would be large enough to be seen from the air, such that CDFG personnel might be able to identify signs of surface disruption between December and March during their monthly aerial salmon redd surveys. If disruption was noted from the air, it would trigger a need for more detailed measurements on the ground. This would eliminate unproductive site visits and thus help minimize project costs. In practice, it turned out that exposed bar surfaces were too small for installation of scour boxes that could be reliably assessed from the air for signs of disruption.

It also turned out that flows in the aftermath of WY 2006 floods rarely receded to levels that would safely permit reoccupation of scour measurement sites (Figure 12). This was an unintended consequence of installing the chains and boxes at exceedingly low flows (between 5,000 and 6,500 cfs). As a result, the monitoring of scour boxes and chains occurred in October, 2006, after flows had receded back to levels that occurred during installation. As a result, observations of scour could not be tied to any specific flow event, but rather reflect the cumulative effects of flow throughout the year.

For each scour measurement site, we retrieved discharge data from the nearest gauging station to identify the peak flow that occurred between the installation and monitoring phases of the study. By correlating the peak interim discharge with observations from the scour boxes and chains, we were able to reduce uncertainties about flow thresholds for bed scour and mobilization.

2.5 Sediment Transport Modeling

We used The Unified Gravel and Sand (TUGS) Model (developed as a separate task of the Sacramento River Ecological Flows Study) to model the mobility of bed sediment and predict changes in surface and subsurface grain-size distributions, including the concentration of fine material in the bed (Cui in press, Cui 2007). The model accounts for the complex interaction of bedload (i.e., sand and gravel) and the bed (i.e., sediment in deposits). Fundamental to TUGS model are the recently developed sediment transport equations of Wilcock and Crowe (2003), who were the first to account for the transport of both sand and gravel on a fractional basis. TUGS model uses a hypothetical relationship to partition bedload (having an estimated quantity and grain-size distribution) into estimated grain-size distributions of the surface and subsurface of the bed. Key model inputs are channel width, slope (Figure 13), the magnitude-frequency distribution of flow and sediment supply, and initial grain-size distributions of the surface and subsurface of the bed.

TUGS model simulates how spawning habitat quality is affected by management actions including flow modifications, gravel mining, and gravel augmentation. It predicts changes in (i) bed elevations, (ii) the concentration of fine sediment in the subsurface (and surface) of the channel bed, and (iii) cross-sectionally averaged grain-size distributions (from which one can estimate D_{50} and other grain size indices). Observations from both the field and from laboratory experiments in a flume indicate that TUGS model generates realistic results (Cui in press, Cui 2007).

By predicting the evolution of particle sizes in the bed of the upper river, our application of TUGS model provides an important test of hypothesis 1—that bed-surface sediment has become increasingly coarse over time since the dams were constructed. By showing how human-induced changes in bed elevations and grain size propagate along the river over time, TUGS modeling results help inform our assessment hypothesis 2—that coarsening has propagated downstream over time.

TUGS simulations were carried forward to 2006 from 1940, and thus reflect the period of sediment supply disruption caused by Shasta and Keswick dams. The model was applied to the reach between Keswick Dam (RM 302) and the mouth of Clear Creek (RM 289.2), with the modeled reach divided into three sections (Figure 14). Bed coarsening is likely to be most pronounced and straightforward to model in this reach due to the paucity of natural coarse sediment supply from tributaries and bank erosion, which would complicate the analysis and interfere with assessing the effects of the dams and the in-stream mining pits. The reach between RM 302–289.2 is also the zone where Chinook salmon spawning is currently concentrated, including the majority of spawning by the endangered winter run.

Initial grain-size distributions of the surface are necessary for modeling how it changes over time, yet field data on pre-dam conditions are not available. For the purposes of our modeling exercises, we estimate that D_{50} initially ranged from 50 to 90 mm, as a function of distance downstream, depending on local channel geometry. This range of D_{50} values is reasonable, given that the goal in this case is to shed light on changes in spawning gravel over time. Our methods for estimating initial conditions of the bed are discussed at length in a separate technical report on TUGS modeling of the Sacramento River (Stillwater Sciences *in preparation*).

Model results were compared against measured grain-size distributions (from both this and previous studies) to see if there are any correlations with observed trends. Precise agreement between observed and predicted grain sizes should not be expected in this case, due in part to a mismatch in scales: TUGS model works in terms of spatially averaged grain-sizes, whereas field measurements of grain size are point-specific, with many measurements required to establish broad spatial averages. In comparing the TUGS modeling results with field data, we focus on relative changes in grain size over broad scales rather than changes in absolute values at individual points. Broad-scale indications of increased grain size over time would generally lend support for the bed coarsening hypothesis.

3 RESULTS AND DISCUSSION

3.1 Spawning Area Surveys

CDWR's initial analysis of the spawning area data from 1964 and 1980 suggested that a large amount of usable spawning habitat had been lost from the upper river (CDWR 1980). However, CDWR’s analysis did not have the benefit of a GIS, which permits a more quantitative assessment of changes in habitat. Here we present results from our new survey, conducted in 2005, along with a revised, quantitative assessment of historical conditions for spawning on the Sacramento River from the 1948, 1964, and 1980 surveys.

Boundaries of spawning areas from each survey were digitized into polygons (e.g., Figure 15 and Figure 16) for calculation of total area used. These areas were then grouped by river mile and summed for analysis of changes over time. The binned results are listed in Table 7 and plotted in Figure 17.

Table 7. Spawning area survey results, upper Sacramento River.

RM	Spawning area (in hectares) by year			
	2005	1980	1964	1948
301	0	0.12	0	0
300	0.15	0.59	0.41	0
299	1.66	1.49	0.00	0
298	3.11	0.67	0.79	3.02
297	1.28	2.43	4.39	4.47
296	3.33	1.20	2.69	1.55
295	0.64	0.67	2.75	1.33
294	0.81	0.11	2.59	0.51
293	0.27	0.36	2.68	1.51
292	0.84	1.06	0.85	2.22
291	1.07	0.92	0.69	1.69
290	0.22	0.29	1.17	0.45
289		2.52	2.05	4.66
288		0.37	2.86	1.70
287		1.75	1.76	2.58
286		0.85	3.68	1.20
285		0.34	1.08	1.87
284		1.09	1.28	0.53
283		0.47	3.02	4.67
282		0.11	0.40	1.65
281		3.97	2.43	3.35
280		0.82	1.10	
279		0.57	0.98	
278		0.63	1.55	
277		0.90	0.00	
276		0.82	0.00	
275		1.82	3.20	
274		1.94	3.49	
273		1.26	4.51	
272		0.00	0.00	
271		3.89	3.50	
270		3.37	2.04	
269		3.68	4.14	
268		0.63	1.77	
267		0.27	0.58	
266		0.75	1.22	
265		0.00	0.00	
264		0.94	1.25	
263		1.02	1.59	
262		0.59	0.90	
261		0.82	0.00	
260		0.10	0.00	
259		0.00	0.00	
258		0.08	1.49	
257		0.31	1.10	
256		0.12	1.15	
255		0.12	0.45	
254		0.06	0.40	
253		0.07	0.00	
252		0.10	0.00	
251		0.27	1.81	
250			0.00	
249			0.31	

Note that 1948, 1964, 1980, and 2005 are the only years with sufficient data for analysis of spawning area. Each whole number river mile reflects area included in the river mile above it (e.g., RM 301 refers to all area from RM 301–302). Cells with no value indicate that habitat mapping is not available for that river mile.

3.1.1 Changes from 1948 to 1964

We refrained from extensive analysis of changes from 1948 to 1964, because 1948 data are based on spawning areas that were measured in the spring rather than at the height of fall-run spawning, as was the case for each of the subsequent surveys. It is nevertheless worth noting that comparisons of the results of the 1948 and 1964 surveys suggest that total spawning area was roughly unchanged for the reach between Keswick Dam (RM 302) and RM 281. The maps also suggest that there were substantial declines in some reaches, including several key spawning riffles. Particularly troubling at the time of 1964 survey was the loss of as much as 2 ha of spawning area at RM 298, the mile-long stretch encompassing Redding Riffle (Figure 15), which appears to be a key salmonid spawning site. Our sediment transport modeling results (discussed at length later in this report) show that an early, dramatic loss of spawning gravel (and thus spawning area) at Redding Riffle would be an expected consequence of the reduction in baselevel that was caused by in-stream mining at Turtle Bay, immediately downstream.

3.1.2 Changes from 1964 to 1980

3.1.2.1 Broad-scale changes

Between 1964 and 1980, observed spawning area of the upper river as a whole (from RM 302 to RM 249) declined by roughly 40%, from 76 ha to 47 ha (Table 7, Figure 17). Nearly 2/3 of the loss occurred in the upper 19 river miles, between Keswick Dam (RM 302) and Anderson Bridge (RM 283). In contrast, losses in the reach downstream of Cottonwood Creek account for just 21% of the total river-wide spawning area loss from 1964 to 1980. This indicates that most of the changes were occurring in the area where other indications of coarsening (discussed later in the report) are present. Losses were especially pronounced from RM 298 to RM 292 (Figure 15; Figure 16) and from RM 288 to 283. This is one of the four major trends highlighted in Figure 17. As originally proposed by CDWR (1980), it is consistent with hypothesis 1—that the bed has coarsened below the mainstem dams, due to the lack of coarse-sediment supply.

3.1.2.2 Effects of tributaries

Spawning area remained roughly stable or increased from 1964 to 1980 within 1–3 river miles of several of the river's sediment-bearing tributaries (Figure 17). For example, the subreach between RM 273.5 and RM 269, which receives abundant sediment from Cottonwood Creek, shows little change in spawning area (Figure 17). In contrast, the subreach between RM 276 and RM 273.5, which has minimal local sediment supply, shows a nearly 50% reduction in mapped spawning area. Similar patterns are evident around Clear Creek, Stillwater Creek, and Bear Creek. Moreover, most of the 10 ha of spawning area that was apparently lost between RM 283 and RM 249 from 1964 to 1980 (Table 7) occurred in reaches that were more than a mile or two downstream of sediment bearing tributaries (Figure 17).

This appears to highlight the importance of sediment loading from tributaries for local maintenance of spawning habitat. The fact that we observe spawning losses just a few miles downstream of the confluences seems to suggest that the scale of coarse sediment loading from tributaries in the upper river is small, at least compared to the overall sediment transport deficit on the mainstem (due to Shasta and Keswick dams). This is corroborated by the available sediment gauging data; the estimated coarse-sediment loading from upper-river tributaries (i.e., those above the Cottonwood Creek confluence) sums to only 6,000 t/yr (Table 8)—only 6% of the estimated pre-dam coarse sediment load of 100,000 t/yr for the upper watershed. Effects of reduced sediment delivery from the tributaries themselves may also be important. Many of the upper river tributaries have been affected by both reduced sediment transport capacity (associated with altered hydrology caused by small dams and water diversions) and/or reduced tributary sediment supply, relative to historical conditions, due to in-stream mining and mining from floodplain sediment sources (Buer 1994). The maintenance of spawning habitat downstream of tributaries is the second of the four major trends highlighted in Figure 17.

Table 8. Average annual sediment yields for tributaries of the Sacramento River.

Location	RM	Drainage area		Bedload[1]		
		mi^2	km^2	Coarse gravel[2] and coarser tons/year	Fine gravel[2] and finer tons/year	Total bedload tons/year
Sacramento R., Keswick[2]	302.0	6,468	16,752	0[3]	0[3]	0[3]
Clear Creek	289.2	228	591	1,000	5,000	6,000
Churn Creek	284.6	12	31	1,000	3,000	4,000
Stillwater Creek	281.1	106	275	1,000	7,000	8,000
Cow Creek	280.1	684	1,772	2,000	17,700	19,700
Bear Creek	277.7	122	316	1,000	3,000	4,000
Battle Creek[3]	271.5	357	925	0[4]	0[4]	0[4]
Cottonwood Creek	273.5	927	2,401	3,000	17,000	20,000
Reeds Creek	244.7	75	194	2,200	13,800	16,000
Red Bank Creek	243.3	94	243	2,700	16,300	19,000
Elder Creek	230.4	136	352	6,800	27,200	34,000
Thomes Creek	225.2	203	526	4,900	57,100	62,000
Mill Creek	230.0	208	539	1,900	500	2,400
Deer Creek	219.5	131	339	2,700	900	3,600

1 In tons/year. This table is for general illustration of relative differences in loading from tributary to tributary; there is considerable uncertainty in the assumptions and calculation methods. Not all of the estimates are based on bedload sampling and few apply to gauges that are near the mainstem. For example, the bedload from Thomes Creek was estimated from suspended sediment at Paskenta, which is 25 miles SW of the confluence with the mainstem.
2 Cutoff between coarse and fine gravel here is 4.8 mm diameter.
3 Bedload is zero below Keswick Dam because it traps all sediment from the upper watershed.
4 Bedload from Battle Creek is assumed to be zero due to its low slope immediately upstream of its confluence with the Sacramento River; the mouth of the creek presumably acts as a coarse sediment trap that minimizes delivery to the mainstem over the short term (CDWR 1980). Over the long term, the sediment load of Battle Creek is probably more substantial (as it must, over time, ultimately pass the sediment delivered to it from upstream sources).
Source: CDWR (1980) and Buer (1994).

By 1980, spawning area had not rebounded at Redding Riffle, despite the injection of a total of more than 13,000 yd3 of gravel within the reach and at sites immediately upstream. Inspection of the spawning area maps (Figure 15) confirms that losses at Redding Riffle continued, with net polygon area declining progressively at the site for each interval from 1948 to 2005.

3.1.3 Changes from 1980 to 2005

3.1.3.1 Effects of gravel augmentation

By 2005 the reach between RM 302 and RM 298 showed an overall net increase of roughly 2 ha in spawning area, relative to what was mapped in 1980 (Figure 17, Table 7). The increase is even bigger (3.7 ha) when the 2005 area is compared to what was mapped in 1964. This is the third of the four major trends highlighted in Figure 17.

The local increase in spawning area by 2005 appears reflect effects of repeated gravel injections at Salt Creek (RM 301) and Keswick Dam (RM 302) since 1988 (Table 9; Figure 18). Most of the spawning area gains occurred between Salt Creek and ACID dam, which probably worked to contain the added gravel (and its biological benefits) upstream (Figure 17; Figure 15). Gravel augmentation appears to have also been especially effective at maintaining spawning habitat in the vicinity of Turtle Bay (CDWR 1981)—where gravel injected into a side channel has presumably been subject to relatively low shear stresses (and thus lower transport rates). This is reflected in the abundance and distribution of polygons mapped in 2005 as part of our gravel study (Figure 15).

Table 9. Gravel Augmentation Volumes by Location and Year, Sacramento River.

Site Name	RM	Volume (m^3)	Year
Caldwell Park	298.3	1,760	1978
Gasline Riffle	298	1,760	1978
Redding Riffle	297.7	6,650	1979
Salt Creek	301	12,230	1988
Keswick	302	6,120	1989
Salt Creek	301	18,350	1990
Dieselhorst	298.8	950	1990
Market St	298.3	8,470	1990
Redding Riffle	297.7	9,590	1990
Turtle Bay West	297.1	11,940	1990
Turtle Bay East	296.6	4,010	1990
Tobiasson	291.6	9,520	1990
Shea Levee	290	13,560	1990
Keswick Dam	302	3,690	1997
Salt Creek	301	12,650	1997
Keswick Dam	302	4,220	1998
Salt Creek	301	7,910	1998
Salt Creek	301	13,180	1999
Keswick Dam	302	4,750	2000
Tobiasson	291.6	12,130	2000
Salt Creek	301	7,910	2002
Salt Creek	301	4,640	2003
Keswick Dam	302	2,240	2004
Salt Creek	301	2,240	2004
Keswick Dam	302	1,900	2005
Salt Creek	301	1,900	2005
Keswick Dam	302	3,160	2006
Grand Total		**187,430**	

Source for pre-1997 data: CDWR 2002 Cow Creek to Jellys Ferry Geomorphic Study
Post-1997 injection amounts are calculated from US Bureau of Reclamation quantities (in tons) with assumed density of 1.45 English tons/yd^3 (with porosity = 0.35 and solid material density = 2.65 metric tons/m^3)

3.1.3.2 Local losses in spawning area

By 1980, spawning area had not rebounded at Redding Riffle, despite the injection of a total of more than 10,000 m^3 (13,000 yd^3) of gravel within the reach and at sites immediately upstream (Table 9; Figure 18). This was apparently due, at least in part, to the fact that roughly 85% of the newly emplaced gravel at Redding Riffle was scoured away by winter and spring floods of 1980 (Parfitt and Buer 1981), before the spawning survey was conducted. Inspection of the spawning area maps confirms that losses at Redding Riffle continued after 1980; by 2005, spawning area had been reduced from a channel-spanning swath to narrow bands along the channel margins (Figure 15), despite additional augmentation efforts in 1990 at the site and immediately upstream (Table 9).

As of 2005, spawning area in the reach bounded by RM 298 and RM 292 was still much lower than it had been in 1964; overall the reach exhibited a loss of about 8 ha—more than half of what was mapped in 1964 (Figure 17; Table 7). This is the last of the four major trends highlighted in Figure 17.

3.1.3.3 Overall loss in spawning area

When the augmentation-related gains above ACID are balanced against the losses from RM 298 to RM 292, mapped spawning area shows a net loss of 5.7 ha from 1964 to 2005 for the analyzed length of river (RM 302 to RM 290), for a 30% loss relative to the total area mapped in 1964. Our analysis suggests that conditions may have been even worse in 1980; total spawning area from RM 302 to 290 was less than 50% of what was mapped in 1964. Although gravel augmentation appears to have improved conditions locally, our analysis and calculations suggest that the upper river continues to harbor substantially less spawning area than it did in 1964. This is not surprising given that the total volume of gravel augmentation, at 187,000 m^3 (or 250,000 yd^3; Table 9), is much lower (by a factor of >14) than the estimated cumulative deficit in coarse sediment supply. This suggests that gravel augmentation has failed to fully offset the ever increasing dam-related deficit in coarse sediment supply. The gravel augmentation volume is also dwarfed by the volume of gravel that has been commercially extracted both from in-stream sources and from the floodplain. This has been an especially important factor in the upper river, because sites below the large, in-stream mining pit at Turtle Bay appear to be isolated from the effects of most of the gravel augmentation efforts, due to the sediment trapping effects of the pit (Figure 18).

3.1.4 Synthesis of spawning area observations

Key observations from the spawning area analysis include:

1. A marked decline in spawning area from 1964 to 1980 from Redding Riffle (RM 298) to RM 292 and from RM 289 to Anderson Bridge (RM 283);
2. Roughly stable or increasing spawning area in the immediate downstream vicinities of the river's sediment-bearing tributaries;
3. Greatly increased spawning area in the uppermost reaches of the river by 2005, due to local effects of gravel augmentation; and
4. Persistence of reduced area from Redding Riffle (RM 298) to RM 292 as of 2005, with a net loss of 30% relative to what was mapped in 1964 for the analyzed subreach (RM 302–290).

Taken together, these observations are consistent with hypothesis 1, but they bear little on hypothesis 2 and even less on hypothesis 3. There have been marked losses in spawning area, except in the immediate downstream vicinities of tributaries and gravel augmentation projects. This implies that spawning gravel has been lost (presumably due to coarsening, as outlined by hypothesis 1), but only to the extent that mapped spawning areas correspond to boundaries of all suitable spawning gravel at each point in time. This assumption is evaluated in the next section for each of the surveys of interest.

3.1.5 Complications due to variability in spawning populations.

Differences in the number of returning adult salmon may have contributed to differences in mapped spawning area in the surveys, but only if returns were so low in one or more of the survey years that suitable gravel area was not "saturated" with spawning fish. Our field-based observations of redds in marginally suitable deposits during the facies mapping work (which will be discussed at length in section 3.2.3) suggest that available spawning area was saturated with fall run spawners in 2006, when the upper river's fall run escapement is estimated to have been about 47,000 fish (Table 10 and Figure 19). The estimated fall run escapement in 2005 was similar, at 45,000 fish (Table 10 and Figure 19), implying that spawning area was probably saturated with fall run spawners during our helicopter survey (which provided the basis for the 2005 data shown in Figure 17). We can reasonably assume that saturation also occurred in the upper river in 1964, when fall run returns on the upper river are estimated to have been roughly 141,000—or 3 times higher than they were when we observed conditions consistent with saturation in 2006 (Table 10 and Figure 19). Importantly, the 47,000-fish threshold for saturation does not rule out the possibility that saturation occurred in 1980, even though only 22,000 fall run spawners returned to the upper river in that year (Table 10). This is because 47,000 is only a minimum bound on the threshold for saturation; our observations suggest it is at least that low, but it could be lower.

Table 10. Populations of returning adult fall-run Chinook salmon, Sacramento River mainstem

Year	Estimated population (thousands)	
	Upper River (RM 302–243)	Middle River (RM 243–163)
1948	40	N/A
1949	50	N/A
1950	111	N/A
1951	73	N/A
1952	267	N/A
1953	408	N/A
1954	276	N/A
1955	231	N/A
1956	85	6
1957	47	12
1958	99	21
1959	250	10
1960	210	14
1961	135	9
1962	116	9
1963	135	7
1964	141	6
1965	99	2
1966	108	3
1967	78	9
1968	96	12
1969	115	18

Year	Estimated population (thousands)	
	Upper River (RM 302–243)	**Middle River (RM 243–163)**
1970	62	6
1971	52	23
1972	34	15
1973	40	17
1974	46	27
1975	52	34
1976	44	36
1977	16	44
1978	32	46
1979	48	65
1980	22	28
1981	26	40
1982	18	23
1983	26	31
1984	37	18
1985	52	42
1986	69	39
1987	77	31
1988	64	18
1989	49	10
1990	32	16
1991	21	10
1992	24	8
1993	33	13
1994	45	14
1995	53	11
1996	72	12
1997	99	21
1998	6	1
1999	133	28
2000	88	9
2001	58	17
2002	46	20
2003	66	23
2004	34	10
[2005]	45	12
[2006]	47	9

Population estimates are based on "in river" data from the Sacramento River. Source: CDFG (2007) except 1948–1955 entries, which are from CDWR (1985). Results from 2005 and 2006 are preliminary.

Available data are insufficient for a conclusive assessment of whether spawning area was saturated in 1980. Even if we assume it was not saturated and neglect results from 1980 entirely, it would have implications for only two of the four main results of the spawning area analysis of Figure 17. Observations in doubt would be (1) that available spawning area decreased from 1964 to 1980 in two key reaches (i.e., from RM 298 to RM 292 and from RM 289 to RM 283), and (2) that spawning area remained roughly constant in the immediate downstream vicinity of tributaries from 1964 to 1980. Conversely, because we can be reasonably certain that the fall run was large enough for "saturation" in 1964 and 2005, the observations that available spawning area (3) increased upstream of ACID by 2005 and (4) decreased by 30% overall from RM 302 to RM 290 would still be valid. Hence, the data would continue to support the main implications of the river-wide spawning area analysis (Figure 17):

- gravel augmentation has been an important contributor to spawning area gains above ACID (RM 298), and
- significant losses have nevertheless occurred from Redding Riffle to at least as far downstream as RM 290

Taken together, these findings are sufficient to support hypothesis 1 from RM 298 to RM 290.

3.1.6 Complications due to fish passage barriers

Fish passage barriers that might have affected spawning area distributions include Redd Bluff Diversion Dam (RBDD) at RM 243.5, the Glenn Colusa Irrigation District (GCID) dam at RM 206 and the ACID dam at RM 298.4. The fact that RBDD was not fully operational in 1964 suggests that some of the apparent loss in upper river spawning returns from 1964 to 1980 (Figure 19) might be due to a barrier-related reduction in passage to the upper river. This is corroborated by the fact that upper river spawning returns declined in the late 1960's and early 1970's, in concert with increases in middle river returns (Table 10 and Figure 19), after RBDD began operating. Hence, the broad-scale spatial distribution of spawning fall-run salmon appears to have been disrupted by RBDD, at least temporarily. However, the extent to which the disruption contributed to reduced upper river returns of the fall run in the late 1970's and early 1980's is unknown. In any case, identifying the mechanism for the decline in returns in the upper reach is not as important as identifying whether the decline occurred (as we have done in Figure 19), and whether it resulted in conditions that were inconsistent with saturation during the 1980 survey. Analysis of RBDD operations unfortunately do not shed light on whether this is the case.

Another potentially more important fish passage issue pertains to the reach upstream of ACID, where spawning area appears to have increased considerably since 1964. It is difficult to verify the extent to which the spawning area gains reflect effects of gravel augmentation and/or effects of recent changes in ACID dam operations, which may have improved access to the reach for the fall run. Based on observations of redd distributions and the abundance of spawning gravel in the reach, most of the observed spawning area gains above ACID are probably due to gravel augmentation rather than changes in passage. As of 1987, winter-run Chinook salmon that spawned above ACID Dam concentrated their redds along the channel margins (Figure 20), implying that suitable gravel and/or hydraulic conditions were not present in the thalweg. This is corroborated by CDWR (1980), who observed that the reach did not contain abundant gravel in 1980. The appearance of channel-spanning spawning dunes during the 2005 fall-run spawning period (Figure 15) implies that both the distribution and the quantity of suitable spawning gravel had changed dramatically as of 2005. Suitable spawning gravel can now be found in the thalweg, as well as along channel margins, despite repeated post-1980 flows above the local threshold for scour of spawning gravel (roughly equal to 36,000–50,000 cfs, according to Parfitt and Buer 1981). The implied gravel sources are the gravel augmentation sites at Salt Creek and Keswick. This strongly suggests that spawning area gains upstream of ACID are due to increases in spawning gravel associated with the gravel augmentation projects.

3.2 Grain-Size Data

3.2.1 Bulk samples

Bulk samples from our 2005 study show a general decrease in median grain size with distance downstream, from 107 mm to 19 mm for the surface and from 29 mm to 12 mm for the subsurface (Figure 21). Armoring therefore decreases with increasing distance downstream; surface samples were 3 to 6 times coarser than the subsurface at the three upper river sites, but only 2 to 3 times coarser than the subsurface in the middle river (Figure 21). This is broadly consistent with what we would expect to see if the bed surface has become increasingly coarse due to an absence of coarse sediment supply, as proposed by hypothesis 1.

3.2.1.1 Comparison of 1995 and 2005 data from the upper river

Bulk sampling methods that we used for our 2005 samples conform closely to those used in 1995 (CDWR 1995) in the upper river. Samples were of comparable size, and were in each case collected from 2.4–2.7 m^2 (8–9 ft^2) surfaces that were selected randomly on point bars between RM 163.2 and 278.5 (Table 2). All samples were collected in the river near the water's edge. Wide scatter in D_{50} across the study reach (Figure 22) indicates there is substantial natural variability in grain size at the local scale (of individual point bars). Moreover, the data are consistent with essentially no change in median grain size over time, although we expect this is due, in part, to the fact that the data from 2005 only partly overlap in extent with the data from 1995 (i.e., from RM 270 to RM 280).[2] Hence, the 2005 bulk sampling data provide for an inconclusive test of hypothesis 1.

In addition to looking for changes in D_{50}, we also looked for changes in fine sediment concentrations, to help inform analysis of hypothesis 3—that the quality of remaining spawning gravel in the upper river has declined in concert with the river's ability to flush fine sediment from the subsurface of its bed. Bulk samples collected from the mainstem above Cottonwood Creek (RM 302–273.5) in 1995 were not heavily contaminated with fine material (CDWR 1995). This implies that fine sediment concentrations were probably not a limiting factor for spawning in the reach. Results from the gravel study help provide the next step in a time series of grain size data for the reach. Figure 23 and Figure 24 show grain-size distributions of the surface and subsurface from bulk sampling in 1995 and 2005 at two sites on the upper river, at RM 275.8 and RM 278.5. Median grain sizes of the surface and the subsurface appear to be essentially the same from one sampling effort to the next in each case. Yet the distributions show a fairly clear coarsening for grain sizes less than about 20 mm (Figure 23 and Figure 24). This coarsening could be caused by one or more of several factors:

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[2] The 1995 data were derived from the upper river (i.e., from RM 302 to RM 273.5), whereas most of the 2005 bulk sampling data were derived from the middle river (i.e., downstream of RM 240; see Table 2), at sites where CDWR collected bulk samples for their 1984 middle river study (CDWR 1984). We chose a middle-river focus in 2005, because bulk sampling is the only practical way to measure subsurface grain size; as a working hypothesis, we expected that changes in subsurface grain size would be more significant from RM 243 to RM 163, relative to changes in the upper river, due to higher rates of sediment supply in the middle river (from bank erosion and tributary inputs). We compensated for the paucity of bulk samples in the upper river by making it the focus of our Wolman count study of changes in surface grain size (see next section). This is appropriate given the upper river focus of hypothesis 1, which pertains to the surface.

- A local decrease in the rate of fine sediment supply during the 1995–2005 period. If the local rate of fine sediment infiltration decreased after 1995 (due to decreased inputs from local bank erosion, for example), then the concentration of gravel and fine sediment in the subsurface might have decreased without any change in the frequency of bed scour.
- Fine sediment transport rates were steady or increased but were accompanied by an increased frequency in bed surface scour that kept the subsurface clean of accumulated sand and silt and mobilized gravel downstream.
- Natural variability in grain size from 1995 and 2005. We attempted to reoccupy geomorphic positions that were sampled in 1995 (see footnote 3), so that the grain-size data would be comparable. Uncertainties resulting from imprecise reoccupation of sampling points are difficult to evaluate but could be significant, given that we observe substantial natural variability in grain size at the scale of individual point bars (Figure 22).

It is difficult to determine which, if any, of the explanations listed above is consistent with conditions at the sites. Importantly, none of the options identifies a mechanism that would be consistent with hypothesis 3. Yet there were only two sets of samples to consider. This is a very small sample size, given the river's reputation for highly stochastic flow and sediment delivery, and given the high natural variability in bed sediment sizes (Figure 22). We therefore suggest that the available bulk sampling data neither support nor strongly contradict hypothesis 3.

3.2.1.2 Incompatibility of data from 1980

CDWR (1995) noted that median grain sizes of bulk samples from 1980 and 1995 exhibit a systematic offset which seems to suggest that samples were coarser by 1995 (Figure 25). We conversely conclude that coarsening in the upper river is *not supported* by the CDWR bulk sampling data from 1980 and 1995, due to differences in the sampling methods that are likely to produce the observed pattern in the absence of any actual increases in surface grain size. The 0.36-m (14-inch) diameter sampler of the 1980 study (CDWR 1980), for example, would have barely fit over many of the upper river's surface particles, which can have diameters as large as 305 mm (12 in) or more. Moreover, the sampling methodology of CDWR expressly ignored deposits consisting of cobbles >200 mm (8 in), because they were deemed too coarse for successful spawning (CDWR 1980). This indicates that sampling was biased toward relatively fine-grained sites in the 1980 sampling effort. Moreover, the small 1980 sampler would have been unable to sample a statistically representative number of particles. In contrast, in 1995, when 3' x 3' plots were sampled, the number of particles in each sample was much larger and statistically robust. Note that, although a distinction was made between "surface" and "subsurface" samples in the 1995 sampling, this was not the case in 1980.

For consistency, we plot the D_{50} of the combined surface and subsurface samples for both data sets (Figure 25). This potentially introduces an additional source of bias to the sampling. Available data suggests that sampling depths were deeper in 1980, relative to what they were in 1995. If so, it may have contributed to the appearance of coarsening in the interval, because the relatively fine subsurface would have contributed more to the overall average in 1980 (compared to 1995), due to the deeper sampling depths. Taken together, the differences in sampling methods for the 1980 and 1995 bulk samples indicate that results from the two sampling efforts are not compatible and are not, therefore, indicative of coarsening over time. For this reason, we ignore results from the 1980 bulk sampling throughout the remainder of this report.

3.2.1.3 Comparison of 1984 and 2005 data from the middle river

Comparisons of bulk sampling data are also problematic for the middle river. The slight offset between 1984 and 2005 data (Figure 26) seems to imply that riffles were coarser on the surface in the middle river in 2005. However, we refrain from suggesting that this is the case due to differences in sampling methods, which could produce the observed pattern without increases in grain size. The 0.6 m by 0.6 m (2' x 2') sampling plot of the 1984 methodology (Buer 1984) may have biased the bulk sampling toward relatively fine-grained sites, and moreover would have been unable to sample enough particles to make D_{50} statistically representative of the site. In contrast, in 2005, when a 0.9-m (3') diameter culvert was used to sample the bed in the middle river, sample sizes were 2 or more times larger than they were in 1984. From a statistical standpoint, this would make the 2005 sampling more robust and less likely to be biased toward fine-grained sites.

3.2.1.4 Synthesis of bulk sampling results

Bulk sampling results can be summarized as follows:

1. Bulk samples exhibit a higher degree of armoring in the upper river, relative to the middle river, consistent with what we would expect to see if coarsening had increased surface grain sizes in the upper river (as proposed by hypothesis 1).
2. Wide scatter in D_{50} across the study reach indicates there is substantial natural variability in grain size at the scale of individual point bars.
3. There are no clear changes in median grain size of either the surface or subsurface from 1995 to 2005 in the upper river. This is due in part to the fact that overlap of the data is minimal.
4. As of 2005, both the surface and subsurface have proportionally more coarse gravel and cobble, and proportionally less fine gravel and sand overall, for two upper river sites where data from 1995 and 2005 overlap. This is suggestive of a loss of relatively fine material (which would stand as direct evidence against hypothesis 3), but we are unable to identify the mechanism for it. It may simply reflect natural variability in grain size, coupled with imprecision in reoccupying sampling sites in successive field efforts.
5. Bulk sampling data from 1980 are incompatible with data from 1995 and 2005, due to differences in sampling methods.
6. Bulk sampling data from 1984 are not 100% incompatible with data from 2005 (due to differences in sampling methods) but nevertheless suggest that median grain sizes became slightly coarser by 2005 in both the surface and subsurface within the middle river.

3.2.2 Wolman counts

3.2.2.1 Local variability in grain size indices and distributions

Wolman pebble counts in 2005 yielded the grain size indexes plotted in Figure 27. All Wolman count sites were at the heads of riffles (on point bars), which means their positioning, from a geomorphic perspective, is similar, both from site to site and from year to year (see footnote 3). Year-to-year changes in grain size should therefore help shed light on both hypothesis 1 and hypothesis 2. Yet, the wide scatter in the grain-size indexes across the study reach indicates there is substantial natural variability in grain size at the local scale (i.e., over the ten- to hundred-meter scale of an individual riffle).

Significant local variability in grain size is further attested by plots of grain-size distributions from the Wolman counts. For example, as shown in Figure 28, the sampling sites at RM 293, which were less than 100 m apart, have differences in median grain size (D_{50}) of nearly 65% (70 mm versus 115 mm). Just half a river-mile farther downstream, at RM 292.5, the median grain size at the head of a riffle is 140 mm (Figure 28). Grain size distributions for all Wolman count sites are provided in plots and tables in the Appendices.

3.2.2.2 Comparison of Wolman counts and bulk samples from 2005

We compared the grain-size distributions from the Wolman counts with data from our bulk samples of the surface for each of the bulk sampling sites. In each case, the distributions determined by the two methods overlap considerably (Figure 29–Figure 31; the full suite of comparisons is provided in the Appendix). The close agreement of the distributions in implies that our Wolman counts provide a realistic assessment of the true (i.e., volumetric) grain-size characteristics of the surface.

3.2.2.3 Changes in grain size at individual riffles

We looked for trends in grain size over time, both at scale of individual riffles (Figure 32–Figure 36) and as a function of distance downstream (Figure 37–Figure 39). At any given point, shifts in grain-size distributions generally show no systematic patterns over time. For example, at RM 275.8 the grain-size distribution first becomes fine, then coarse, and then fine again, relative to baseline conditions of 1980 (Figure 32). Figure 33–Figure 36 show cases of grain size eventually becoming coarser, after interim shifts toward exceedingly coarse (Figure 33) or relatively fine distributions (Figure 34 and Figure 36).

Precisely what these changes represent is unclear. They could reflect local changes in sediment supply and transport and may be related to the system-wide shutdown of sediment supply due to the dams. Yet we cannot rule out the possibility that the apparent changes in grain size merely result from our inability to collect samples from exactly the same point in successive field efforts, due to uncertainties in sample locations. Errors in sample placement mean that comparisons of grain-size data across time will reflect natural variability in grain size, in addition to any changes caused by deficits (or surpluses) in the sediment supply. On the relatively small scale of individual point bars, the natural variability in grain size may be big enough (e.g., Figure 28) to account for all of the observed variations in grain-size distributions at individual points over time (Figure 23 and Figure 24, and Figure 32–Figure 36).

In some cases, however, the coarsening and fining from time-step to time-step is roughly consistent with what we would expect, given what we know about local sediment supply conditions. For example, the decrease in grain size between 1980 and 1995 at RM 289.2 (Figure 34) might have something to do with the sample's proximity to Shea Levee (RM 290), where CDWR and CDFG added nearly 13,700 m^3 (18,000 yd^3) of spawning gravel in 1990 (Figure 18; Table 9; Bigelow 1996). If so, then the lack of further gravel augmentation at Shea Levee after 1990 would be consistent with the apparent coarsening between 1995 and 2005. The initial "fining" and subsequent "coarsening" of RM 298.3 (Figure 36) might similarly reflect the effects of the one-time additions of gravel at Dieselhorst (RM 298.8) and Market St. (RM 298.3) in 1990 (Figure 18; Table 9). We nevertheless maintain that local variability in grain size can explain all of the temporal variations at the individual riffles (Figure 23 and Figure 24, and Figure 32–Figure 36) just as well.

3.2.2.4 Changes in grain size over the subreach scale

Natural variability in grain size is also reflected in a broad-scale perspective of median grain size for the upper river (Figure 37), the middle river (Figure 38), and the study area as a whole (Figure 39). Moreover, the later data sets (from 1995, 2001, and 2005) fall entirely within the limits of the earliest sets from 1980 (Figure 37) and 1984 (Figure 38). Hence, systematic increases in average grain size over time, if present, are subtle enough that they are not readily visible from the data.

Changes in median grain-size over time

To investigate whether there have been any statistically significant changes in grain size over time, we conducted non-parametric regression analyses on data from each timestep, to establish the slopes and confidence limits of the relationship between grain size and river mile. Non-parametric regression analysis is a non-linear approach to assessing the relationship between one factor and another (in this case, grain size and river mile). Regression statistics at a given point are determined using nearby observations that are weighted according to distance from the point, out to a maximum "bandwidth" (e.g., Bowman and Azzalini 1997). The bandwidth defines the limits of the regression for each point and is optimized iteratively, along with the distance-weighting scheme, as part of the analysis[3]. We preformed the analyses on log D_{50}, a measure of central tendency for grain-size distributions, and the ratio of log D_{84} to log D_{16}, a measure of dispersion or spread (i.e., the variance) for grain-size distributions.

The relationships between log D_{50} and distance for each timestep are plotted in Figure 40 with 95% confidence limits. Inspection of the plots reveals that the 2005 relationship is offset vertically toward slightly higher grain sizes relative to those of previous years (Figure 40). This would be consistent with coarsening in the upper river. We performed a series of pair-wise comparisons of regression statistics (Table 11). Our results for log D_{50} versus river mile reveal:

- the 1980 regression is not statistically different from the 1995 regression,
- the 2005 regression is different from both the 1980 and the 1995 regressions, and
- the 2001 regression is not detectably different from any of the other regressions.

This confirms, from a statistical standpoint, that median grain sizes in 2005 were coarser, on average, than they were in previous years. This is consistent with hypothesis 1—that the quantity of spawning gravel has been decreasing over time, due to bed-surface coarsening associated with in-stream mining and dam-related reductions in sediment supply. The indication that 2001 is not different from other years (within uncertainties), coupled with the fact that 2001 data cover a limited stretch of river, from Anderson Bridge (RM 283.3) to Jellys Ferry (RM 266), suggests that coarsening may be restricted to the reach upstream of RM 283. Hence, our statistical analysis of the Wolman pebble count data is sufficient to support hypothesis 1 for the stretch of river bounded by RM 283.5 and RM 298.3 (the upstream limit of the samples). This is consistent with the spawning area analysis (section 3.1), which, due to data limitations, suggested a somewhat less extensive reach of coarsening from RM 298 to RM 290. Because a coarser bed is also less prone to scour, the Wolman count analysis also provides indirect support hypothesis 3—

[3] We used the "normal optimal" approach (Bowman and Azzalini 1997) for bandwidth selection in our grain size analyses.

that the quality of any remaining spawning gravel in the upper river has declined due to reductions in bed surface mobility.

Table 11. Pair-wise comparisons of regressions of grain-size characteristics versus river mile.*

Parameter	Years	Number of observations	RM coverage	significance (p) evaluated at bandwidth = h				
				h=2	h=5	h=10	h=20	h=100
log D_{50}	'80 vs. '95	34 vs. 19	273.1–298.3 (25.2)	0.966	0.980	0.924	0.886	0.848
log D_{50}	'80 vs. '05	45 vs. 21	264.6–298.3 (33.7)	0.494	0.122	**0.046**	**0.046**	**0.044**
log D_{50}	'95 vs. '05	19 vs. 20	273.1–298.3 (25.2)	0.266	0.076	**0.022**	**0.038**	**0.046**
log D_{50}	'80 vs. '01	20 vs. 12	266.2–283.5 (17.3)	0.554	0.378	0.304	0.274	0.314
log D_{50}	'95 vs. '01	9 vs. 8	273.1–283.5 (10.4)	0.418	0.270	0.246	0.230	0.220
log D_{50}	'01 vs. '05	12 vs. 8	266.2–283.5 (17.3)	0.988	0.812	0.540	0.438	0.418
log D_{84}/D_{16}	'80 vs. '95	34 vs. 19	273.1–298.3 (25.2)	0.368	0.180	0.120	0.092	0.094
log D_{84}/D_{16}	'80 vs. '05	45 vs. 21	264.6–298.3 (33.7)	0.190	**0.040**	**0.014**	**0.002**	**0.010**
log D_{84}/D_{16}	'95 vs. '05	19 vs. 20	273.1–298.3 (25.2)	0.078	**0.044**	**0.038**	**0.038**	**0.040**
log D_{84}/D_{16}	'80 vs. '01	20 vs. 12	266.2–283.5 (17.3)	0.228	0.204	0.194	0.152	0.150
log D_{84}/D_{16}	'95 vs. '01	9 vs. 8	273.1–283.5 (10.4)	0.238	0.146	0.126	0.162	0.128
log D_{84}/D_{16}	'01 vs. '05	12 vs. 8	266.2–283.5 (17.3)	**0.026**	0.524	0.798	0.884	0.908

significant at 95% confidence level

significant at 90% confidence level

*Permutation tests, B=500; methods based on Bowman and Azzalini 1997

Changes in the spread of grain size distributions over time

For an indication of whether there have been any changes in the spread of grain-size distributions over time, we performed pair-wise comparisons of regression statistics from the analyses of the ratio of log D_{84} to log D_{16} versus river mile (Table 11). Our results reveal

- highly significant differences between 1980 and 2005 and between 1995 and 2005 for bandwidths ≥ 5–10 river miles,
- highly significant differences between 2001 and 2005 for bandwidths = 5 river miles, and
- slightly significant differences between 1980 and 1995 for bandwidths ≥ 20 river miles.

Taken together, the results from our pair- wise comparisons suggest there has been a progressive reduction in the variance of grain size distributions on the upper river over time.

What does this represent? On the one hand it could reflect a decrease in the maximum grain size of deposits. We might expect to see such a change if sediment loading were high enough that it could swamp the bed and cover coarse armor deposits with sand and gravel. This seems unlikely given the paucity of sediment sources in the upper river, and given that it would lead to a reduction in D_{50} (in sharp contrast to what we observe).

Alternatively, the apparent decrease in the spread of grain-size distributions could reflect the effects of winnowing (i.e., the selective transport of relatively fine material), which would tend to reduce the abundance of fine material in deposits without any change in maximum grain size. This would lead to coarsening of median grain sizes, as observed from 1980 to 2005 and 1995 to 2005, based on statistical comparisons of D_{50} versus river mile (Table 11; see discussion above). Some degree of winnowing should be expected in the post-dam era, given that sediment mobilizing flows have continued to occur in the absence of significant sediment loading. Hence, we suggest that the decrease in the spread of grain-size distributions reflects the progressive loss of relatively fine material from deposits over time. This provides a mechanism for the progressive coarsening proposed in hypothesis 1.

3.2.2.5 Synthesis of Wolman count results

Wolman count results can be summarized as follows:

1. Wolman counts show wide scatter in D_{50} across the study reach. This indicates there is substantial natural variability in grain size at the scale of individual point bars.
2. Our time-series of grain-size distributions suggest that changes in grain size are erratic, with coarsening at some sites and fining at others. This may simply reflect natural variability in grain size, coupled with imprecision in reoccupying sampling sites in successive field efforts.
3. Statistical analysis shows that median grain sizes were coarser in 2005 than they were in previous years for the reach bounded by RM 298 and RM 283.5. This is consistent with hypothesis 1—that the quantity of spawning gravel has been decreasing over time. It is also consistent with hypothesis 3—that the quality of any remaining spawning gravel in the upper river has declined due to reductions in bed surface mobility.
4. Statistical analysis shows that the dispersion in grain size distributions has become smaller over time for the reach bounded by RM 298 and RM 283.5. This implies that the increases in median grain size (presented as result #4) are the result from winnowing—the selective transport of relatively fine material (i.e., coarse gravel and fine cobbles) from sediment deposits.

3.2.3 Facies maps

Whereas Wolman pebble counts and bulk samples provide localized measurements of grain size in shallow water areas, facies maps document reach-wide variations in the dominant grain-size characteristics of the bed. At the time of the facies mapping work, we made detailed observations of the locations and extent of salmonid spawning at each of the study sites. When coupled with older spawning area data from the spawning atlases of CDWR, the facies mapping work helps tell a story of local losses and gains from time step to time step at the local scale of the facies mapping study sites. We are able to then interpret the losses and gains on a case-by-case basis, in terms of whether sediment sizes and hydraulic conditions of the bed are suitable for spawning, based on our facies mapping results. This helps make the facies mapping a powerful tool for evaluating changes in spawning area over time.

We selected our sites to shed light on why spawning has persisted in some places and not in others, using the time series of spawning area maps (i.e., from 1948, 1964, and 1980) for guidance (Figure 17; Table 12). All of the facies mapping work was conducted in December 2006. The vast majority (~90% or more) of surveyed area at each site was submerged at the time of the field work.

Table 12. Area of mapped spawning by year for each facies mapping site.

Year*	Area (in ha) by facies mapping site				
	F1	F2	F3	F4	F6
1948	2.8	0	1.7	1.7	3.9
1964	1.9	0.33	1.2	1.4	4.4
1980	2.0	0.29	0.9	1.1	2.1
2006**	2.4†	0.16	1.1	0.6	1.1

* estimates from 1948, 1964, and 1980 are based on GIS analysis of historical spawning area data; 2006 data are from field-based observations of active spawning during facies mapping work.
** 2006 data are based on direct field observations made during the facies mapping exercise
† for estimates of spawning area in the right, side channel at F1, we used observations from the 2005 aerial survey video to complement data from the direct observations of spawning during the facies mapping exercise.

Facies maps for each of our five sites are presented in Figure 41–Figure 45. We highlight key results and observations from each site in the sections below, focusing on facies-to-facies variability in four results:

1. median particle size,
2. percent occurrence of each dominant and qualifying subordinate size class,
3. percent of the surface covered by particles greater than 130-mm diameter (assumed in this case to be the coarsest movable particle for salmon of the Sacramento River), and
4. presence/absence and spatial extent of redds at the time of the mapping.

We then assess approximate uncertainties inherent in the facies mapping results by comparing our visual estimates of grain size with available Wolman count data from the facies.

3.2.3.1 Facies 1 (RM 287.7)

Facies map 1 (F1) centers on the left branch of a bifurcated stretch of channel at RM 287.7 (Figure 41). We divided F1 into 12 distinct facies with median grain sizes ranging from 32 mm in one small patch (covering just 1% of the area) to 180 mm in two separate patches (which together cover 17% of the area). Most of the facies were almost exclusively dominated by cobbles. We estimate that roughly 59% of the total area mapped is too coarse for spawning, due to ≥40% coverage by immovable material, assumed in this case to be particles with estimated diameters >130 mm.

Aerial redd mapping and field observations at F1 indicate:

- extensive spawning from time step to time step over the entire period of record (Table 12), and
- shifts over time in the locations of the heaviest spawning (Figure 41).

This is broadly consistent with our interpretation of available air photos and historical channel alignments (CDWR 1980), which suggest growth and upstream migration of the mid-channel island in apparent response to gravel mining along the outside bank of the left branch.

We selected the site to investigate the cause of a recent shift in spawning from a spot near facies polygon 9 (F1-9) in 1980 to rows of dunes spanning polygons 3, 4, and 5, at the head of the mid-channel island in both 2005 and 2006. The 1980 spawning area is now characterized by a D_{50} of 110 mm and a percent coverage by particles >130-mm diameter of 40%. This coverage by presumably immovable material appears to be too high to support successful redd building. In contrast, the current spawning site (i.e., upstream of the old site) has a finer bed, with percent coverage of particles >130–mm diameter ranging from just 15 to 25% across polygons 3, 4, and 5. This is presumably too little coarse material to preclude spawning at the site. Taken together, the facies maps and spawning area maps are consistent with our general expectations about the requirements of spawning gravel in the river—i.e., that successful redd-building by Sacramento River salmon is difficult or impossible in deposits that are ≥40% covered by grains with diameters >130 mm.

Our observations suggest that the position of prime spawning gravel have shifted, but without any clear signs of dam-related coarsening (which would be expected to affect the reach as a whole). The observed changes in morphology of the island and the shifts in prime spawning gravel across the site are not surprising, given that the Clear Creek confluence and the Shea Levee gravel augmentation site are just upstream and have presumably been important local contributors of sediment (especially between 1980 and 2005, when augmentation was occurring). The shift may also be related to localized effects of the large mining pit just upstream of the facies mapping site.

In summary, observations from facies mapping site 1 seem to corroborate indications from the spawning area analysis (Figure 17)—that sediment supply from tributaries and gravel augmentation can locally offset the effects of reduced sediment supply in the mainstem. If this is the case, then it implies that augmentation should continue, to ensure maintenance of available spawning area in the future. They do not, however, conclusively test any of the study hypotheses, because the gain in spawning area appears to reflect the effects of tributary inputs and/or gravel augmentation, which overwhelm the effects of the overall sediment supply deficit and thus confound our analysis of its effects on gravel quality and quantity. We hereafter refer to the effects of gravel augmentation, tributary confluences, and other local sediment sources as "confounding" effects.

3.2.3.2 Facies 2 (RM 290.8)

Facies map 2 (F2) covers a relatively straight stretch of channel at RM 290.8 (Figure 42). Across the 8 mapped facies, estimated median grain size ranged from 40 to 250 mm but was mostly coarser than 100 mm. We judged roughly 93% of the bed to be too coarse for spawning, with >50% coverage by particles with intermediate diameters >130 mm. This is consistent with the observed absence of spawning in most of the reach.

All of the current spawning in F2 occurs in polygon 8 (F2-8), in a series of linear dunes that extend about 20 m from the bank. The dunes are immediately downstream of a gravelly bank with obvious signs of recent erosion. Farther upstream, in F2-7, where the channel margin is too coarse for spawning (i.e., with more than 40% immovable particles), the bank has been armored against erosion by rip rap. Spawning is similarly absent along the rip-rapped bank downstream of F2-8, although it was apparently abundant enough to map there in 1980 (Figure 42), before the revetment (and the house it protects) was built. Taken together, these observations highlight the importance of bank erosion and other local sediment sources for long-term maintenance of spawning gravel. They also suggest that installation of bank armor may have a significant, adverse, local effect on spawning gravel along channel margins. In general, much of the upper Sacramento River is bounded by bedrock or other erosion-resistant material (CDWR 1980), such that supply of material from bank erosion is far too little to offset the overall deficit of coarse sediment supply from sources blocked by Keswick Dam at RM 302.

Of particular interest in our study of F2 was explaining the disappearance of spawning area from the middle of the reach after 1964. The historical spawning patch spans what we mapped as two separate facies, F2-5 and F2-6, which have estimated median grain sizes of 110 and 70 mm, respectively. In the case of F2-6, the bed was less than 10% covered by immovable particles. Based on our conception of the size limits of spawning gravel for Sacramento River salmon, we would argue that F2-6 should be an ideal site for redd-building. The absence, in this case, can be explained by unsuitable hydraulic conditions in the patch. At the time of the field work, in December 2006, flow depths throughout the polygon were less than 15 cm—too shallow for access by the river's Chinook salmon. Even if they could access the polygon, we suspect that the velocities we observed (estimated to be <0.3 m/s) would be too slow for delivery of sufficient oxygen to salmonid egg pockets at depth. Upstream, in F2-2, where hydraulic conditions appear to be better, spawning is nevertheless absent, apparently because the bed is too coarse, with an estimated D_{50} of 160 mm and 60% percent surface coverage by immovable particles. As for how the patch in F2-6 supported spawning in 1964, we speculate that local hydraulics may simply have been better in 1964. In any case, we suggest that our observations from F2-6 highlight the importance of a convergence of suitable hydraulics and grain-size characteristics on the bed.

In summary, observations from facies mapping site 2

- highlight the importance local hydraulics on the presence/absence of suitable spawning gravel, and
- indicate that spawning habitat can be maintained locally by coarse sediment inputs from bank erosion.

They do not, however, provide for a conclusive test of any of the study hypotheses, because the loss in spawning area from 1964 to 2005 may have been due to an absence of suitable hydraulics rather than changes in grain size over time.

3.2.3.3 Facies 3 (RM 291.4)

Facies map 3 (F3) centers on the downstream portion of an actively eroding meander bend in the main branch of a bifurcated reach at RM 291.4 (Figure 43). We divided F3 into 11 facies polygons, with estimated median grain sizes ranging from 50 to 200 mm. The site is dominated by a coarse, cobble bed, with only about 33% of the area having median grain sizes less than 100 mm, and roughly 66% of the area having 40% or more coverage by grains with estimated diameters > 130 mm.

The most important observation from F3 was the presence of redds in several small deposits of gravel along the channel margin, in facies F3-4 and F3-9. It indicates that fish were spawning wherever they could, irrespective of deposit size, presumably because suitable gravel deposits were effectively saturated with spawning fish at the time of the field work in 2006. Given that the estimated fall run returns for 2005 and 2006 are roughly equal (Table 10 and Figure 19), we can be reasonably certain that spawning area was also saturated with fall run spawners during our helicopter survey (which provided the basis for the 2005 data shown in Figure 17). Saturation probably occurred in the upper river in 1964, when fall run returns where 3 times higher than they were in 2006 (Table 10 and Figure 19).

Field observations in 2006 confirmed the 2005 aerial assessment of abundant spawning in polygon 1 (F3-1), at the head of the island where the channel bifurcates. Large spawning patches were also observed there in 1964 and 1980, but not in 1948 (Table 12). Observations of bed material in F3-1 confirm that it appears favorable for spawning, with an estimated median grain size of 90 mm, and only 15% of the area covered by particles with intermediate diameters in excess of 130 mm. Hydraulic conditions are also apparently favorable because of the bifurcation, which shunts part of the river's flow through the right branch of the channel. Historical channel alignments from the CDWR spawning atlas (CDWR 1980) indicate that the bifurcation had developed by 1938, and that the current planform shape of island was more or less established by 1952. We can thus confirm that the lack of spawning at the head of the island was not due to an absence of a bifurcation. An alternate explanation for the absence of spawning at the island head in 1948 is timing of the survey; the 1948 survey was conducted in the spring, not at the height of the fall run like the other surveys.

Of particular interest at F3 was the area below the apex of the bend, in the left branch, where several spawning patches were present along the channel margins in 1980, but later absent according to both the 2005 helicopter survey and the 2006 facies mapping field work. One patch falls within polygon 8 (F3-8), which has an estimated median grain size of 150 mm and 50% coverage of "immovable" grains, consistent with unfavorable conditions for spawning. The second patch falls within F3-5 and the third is located in F3-3. In both polygons, D_{50} is estimated to be >150 mm and >60% of the bed appears to be covered by coarse, immovable grains. These observations suggest that the spawning areas of the 1980 channel margins have become too coarse for spawning as of 2006. For the reach as a whole, the area of mapped spawning has been essentially unchanged since 1964 (Table 12). Hence, the reach also lacks evidence for dam-related coarsening.

Analysis of the aerial surveys and field observations from F3 highlight an important caveat that needs to be considered in interpretation of the spawning area analysis (section 3.1) and the facies mapping results: the potential for errors in mapping of redds from the air. In F3-2, along the inside of the bend, the 2005 aerial survey showed only a few short (<5-m-long) dunes extending out from the bank, whereas field observations from 2006 indicate spawning is occurring there in at least six dunes that extended well beyond the mapped limits from 2005 and past the channel centerline in some cases (Figure 43). An extensive patch of spawning was observed at this spot from the air in 1948, but not in 1964 or 1980. Given the discrepancy between what we would map from the video of 2005 and what we observed on the ground in 2006, we were forced to consider throughout this analysis whether aerial mapping provides, at best, only a rough estimate of the spawning area used at any given time on the river. If this is true, it might explain why spawning wasn't observed from the air in 1964 or 1980 at F3-2, and thus seems to suddenly reoccur there in 2005 and 2006 for the first time since 1948. An alternate interpretation of the discrepancy between the mapped 2005 and 2006 spawning areas in F3-2 is that the 2005 area actually grew in the intervening period due to a supplement of gravel from upstream. This is difficult to evaluate in the absence of additional data. Our inclination is to treat the discrepancy as an indication of the imprecision of the methods. As such, it implies that small changes in local spawning area are difficult to detect with certainty from year to year using the methods employed in this study.

Interpreting the results from F3 is complicated by the potential effects of in-stream mining and gravel augmentation in the reach. The mapping area encompasses the Tobiasson gravel augmentation site (at RM 291.6), where a total of roughly 27,000 m^3 of gravel was added in two separate injections, in 1990 and 2000 (Figure 18), to counteract the effects of historical in-stream mining in the reach. We suspect that most of this gravel has been delivered to F3-11 and points farther downstream from the installation site along the outside bend of the meander. As for why the area in F3-2 was lost after 1948, we can only speculate. Given that in-stream mining was historically significant enough to eventually warrant remedial augmentation measures, it seems reasonable to guess that in-stream mining may have contributed to the loss. This is difficult to confirm in the absence of quantitative data on the timing and volume of mining extractions in the reach. If much of the extraction occurred between 1948 and 1964, then it would be a likely cause of the temporary absence of spawning at F3-2.

In summary, observations from facies mapping site 3

- reveal the presence of redds in deposits that would be considered marginally suitable, at best, implying that virtually all usable spawning gravel was in use by the fall run during the mapping (a necessary condition for saturation in 2006, 2005, and, by extrapolation, 1964; Figure 19; Table 10); and
- highlight the potential for errors in mapping of redds from the air by showing that our field observations (from 2006) differ from what we mapped based on the 2005 helicopter survey, when fall run returns were similar (Figure 19; Table 10).

They do not, however, provide a conclusive test of any of the study hypotheses, because the overall stability in spawning area from 1964 to 2005 may reflect the offsetting effects of gravel augmentation at Tobiasson in 1990 (Table 9; Figure 18), which confound analysis of whether the dam-related deficit in supply would have led to coarsening in the reach. If this is the case, then it implies that augmentation should continue, to ensure maintenance of available spawning area in the future.

3.2.3.4 Facies 4 (RM 292.7)

Facies map 4 (F4) covers the downstream end of a meander, along the inside bend near RM 292.7 (Figure 44). The outside of the bend is armored by rip rap. We divided the area into 7 facies, with estimated median grain sizes ranging from 25 to 165 mm. The assemblage of facies at F4 were relatively fine, compared to those of the other facies map sites; only 52% of the bed was judged to be more than 40% covered by immovable particles, and roughly 13% had gravel as a dominant facies.

Aerial redd mapping and field observations indicate that the spawning area along the channel margin in the reach was historically extensive but has been reduced progressively from a high of 1.7 ha in 1948 to just 0.6 ha in 2006 (Table 12). Inspection of the historical maps indicates that much of the lost area once fell in what we mapped as polygon 1 (F4-1), where coverage by immovable grains is now estimated to be 65 to 70% of the surface. This indicates that the loss of spawning area may be related to coarsening in the reach.

We observed abundant quartzite particles on the bed surface at the site. Quartz is not naturally abundant in mainstem stream sediment this far up in the watershed. The presence of quartzite therefore indicates downstream delivery of gravel from augmentation projects (Figure 18), which used the material as an exotic tracer for monitoring sediment transport. The fact that manually injected material has supplemented the gravel at F4 implies that spawning area losses would likely have been greater than observed in the absence of gravel augmentation upstream.

We observed little spawning in F4-3 and F4-5, even though grain sizes appear to be suitable for spawning. Field observations suggest that hydraulic conditions may be limiting in those polygons, much as they appeared to be in F2-6, at facies map site 2. F4-6 was covered in silt and F4-7 was too deep for a reliable visual assessment of grain size.

The reach has been largely isolated from plausible benefits of gravel augmentation because it is downstream of the remnant mining pits at Turtle Bay (RM 297) and Kutras Park (RM 296), which presumably trap most of the sediment from the river's main injection sites (Figure 18). The site is also upstream of all of the sediment bearing tributaries of the upper Sacramento River (Table 8). The absence of lateral planform change since at least 1952 in this and adjacent upstream reaches (based on maps provided in the CDWR 1980 spawning atlas) further implies that local gravel inputs from bank erosion have been minimal. Hence, changes in spawning area in this reach can be explored without the potentially confounding effects of local sources of coarse sediment supply.

Spawning area at F4 declined from 1.7 ha in 1948 to 1.4 ha in 1964. It then dipped further to 1.1 ha by 1980 and was only 0.6 ha as of 2006, during the facies mapping exercise (Table 12). This progressive loss of nearly two-thirds of the historical spawning area is too large to be explained by uncertainties in the spawning-area analysis. When coupled with our observations of a coarse, immovable bed in areas that supported spawning in previous surveys (Figure 44), the progressive 67% decline in spawning area at the site provides clear support for hypothesis 1, suggesting there has been continued coarsening in the upper river, presumably due to the systemic, dam-related reduction in coarse sediment supply. By extension, it also supports hypothesis 3—that the quality of remaining spawning gravel has declined due to reductions in bed-surface mobility.

The apparent inward migration of the edges of mapped spawning on the inside (i.e., point-bar-supporting) bend of the meander at the golf course site (Figure 44) is consistent with the suggestion (CDWR 1995) that spawning is now confined to relict features (such as fossilized point bars), in zones where local hydraulics prevent high flows from eroding gravel. It is also consistent with the notion that these relict features are becoming increasingly scarce due to the effects of high, bed-mobilizing flows that continue to occur—if at a somewhat reduced frequency—in the post-dam era of flow regulation.

3.2.3.5 Facies 6 (RM 297.5)

Like F4, facies map 6 (F6), which is centered on Redding Riffle (at RM 297.5), paints a fairly clear picture of spawning area losses resulting from reach-scale coarsening associated with systematic sediment-supply deficit. We divided F6 into 8 polygons with estimated median grain sizes ranging from 50 to 195 mm (Figure 45). Two facies with gravel-dominated substrates (F6-1 and F6-4) occur in thin bands along the channel margins. An additional cobble-dominated facies (F6-2) with apparently suitable spawning material (i.e., D_{50} = 80 and %>130 mm = 12.5) occurs along the edge of F6-1. Almost all of the current spawning occurs in those three facies. The remaining 78% of the mapped area is estimated to have >40% coverage by particles with intermediate axes diameters >130 mm. In F6-3 and F6-8, the gravel that does occur is likely sourced from historic gravel additions on the right channel bank and appears to be little more than a thin veneer over an otherwise exceedingly coarse bed. This presumably renders it unsuitable for spawning. Of the spawning area mapped along the right bank in 2006, only the downstream half is considered viable. The rest consists of dunes that were dewatered at the crests and covered in organic material in the troughs at the time of the field work.

Redding Riffle was historically renowned for its heavy concentrations of spawning salmon. The time series of spawning maps confirms that the reach supported a channel-spanning swath of redds in 1948 and 1964 (Figure 45). Yet, by the mid of the 1970s, low spawning returns were worrisome enough that CDFG began augmenting spawning gravel supply in the reach (Parfitt and Buer 1981). In 1978, approximately 3,700 m^3 of added gravel was split between Caldwell Park, a quarter of a mile upstream, and Gasline Riffle, three quarters of a mile downstream (Figure 18). These augmentations were ultimately judged to be ineffective, due to hydraulically unfavorable conditions at the installation sites (Parfitt and Buer, 1981). In 1979, an additional 6,700 m^3 of spawning-sized gravel was added at Redding Riffle itself, in a ~50-cm-thick, 1.2-ha-area veneer along the right bank (Figure 18; Parfitt and Buer, 1981). As indicated earlier, this augmentation also turned out to be largely ineffective after high flows in the winter of 1980 scoured away an estimated 85% of the added material (Parfitt and Buer, 1981). As of the fall of 1980, when the aerial spawning survey was repeated, spawning area in the riffle was reduced by a factor of more than 2, from a high of 4.4 ha in 1964 (Table 12). It seems likely that the reduction would have been even greater in the absence of augmentation activities in 1978 and 1979. As of 2006, during our facies mapping field work, the occupied spawning area had shrunk to just 1.1 ha (Table 12), despite the 1990 injection of roughly 19,000 m^3 of additional gravel at Redding Riffle, Market Street (near Caldwell Park), and Dieslehorst (just upstream of Caldwell Park) (Bigelow 1996, see also Figure 18). The thin strip of suitable spawning gravel mapped along the channel margin in F6-4 is a remnant of the gravel additions at Redding Riffle. Taken together with results from the facies maps, the marked, progressive loss of habitat at Redding Riffle appears to reflect the effects of reach-wide coarsening associated with the systemic, dam-related deficit in coarse sediment supply.

Hence, notwithstanding the apparent local success of the Salt Creek (RM 301) and Keswick Dam (RM 302) gravel injections, observations from Redding Riffle (RM 297.5) indicate that gravel augmentation alone does not always preclude coarsening-related losses in spawning areas—even when gravel is added repeatedly in large volumes. The observed extent of spawning at Redding Riffle has declined progressively over time to roughly 25% of the maximum observed in 1964 (Table 12). This is consistent with the facies maps, which show that bed sediment has become too coarse for spawning throughout much of the reach (Figure 45). Given the lack of other sources of coarse sediment in the reach, it seems clear that losses in spawning area at Redding Riffle would have been even greater than observed in the absence of local gravel augmentation. Taken together, results from F6 are consistent with hypothesis 1 and hypothesis 3.

3.2.3.6 Constraints on the size and abundance of immovable particles

The observations highlighted above emphasize local changes in spawning area and grain size from site to site over time. We can also use the combined results of the facies mapping and spawning area assessments, in a more general river-wide analysis, to test our working hypothesis about the upper limits of particle size for spawning Chinook salmon of the Sacramento River. The working hypothesis, introduced in section 1.2.1, is that salmon are generally not able to successfully spawn in deposits where more than 40% of the surface is covered by particles bigger than the largest movable particle—assumed to be 130 mm in b-axis diameter in this case, based on observations from the nearby Feather River. Our observations from the Sacramento River provide for effective evaluation of this hypothesis, because the mapped facies span wide ranges in both spawning intensity and percent coverage by coarse (presumably immovable) particles (Figure 41–Figure 45).

In Figure 46, we plot the percent of area used by spawning fish on the Sacramento River in 2006 against the percent of area covered by particles with intermediate axis diameters >130 mm for each of the facies. An upper threshold on spawning appears to occur when the bed is more than 40% covered by coarse particles. This corresponds with expectations based on the working hypothesis derived from observations of spawning in the Feather River. Yet Figure 46 also shows that spawning is scarce or absent for several facies with much lower coarse particle concentrations. While we would judge these facies to be suitable on the basis of grain size, hydraulic conditions in at least a portion of many of the facies (plotted as stars and triangles in Figure 46) were not favorable for spawning at the time of the field work. In some, the apparently suitable material was completely dewatered due to low-flow conditions at the time of the mapping. In others, water depths were too shallow or velocity was too slow to plausibly support spawning. This suggests that future studies should be able to improve understanding of the relationship between spawning suitability and grain size (Figure 46) by delineated facies according to hydraulic characteristics as well as grain size, with the help of field estimates of water depth and velocity. Yet, even in the absence of such refinements, the results shown in Figure 46 support our hypothesis about the upper limits on grain size for spawning suitability.

Indications that the hypothesis is reasonable are further corroborated by grain-size distributions for the 12 Wolman counts that were conducted during the facies mapping exercise (Figure 47). Four of the distributions (marked with blue lines in Figure 47) are from within facies that were either being actively utilized for spawning at the time of the mapping (as in the case of F1-3, F3-1, and F4-4), or were judged highly suitable but nevertheless lacked spawning due to poor hydraulic conditions (as in the case of F2-6). All of the "suitable" sites have relatively fine grain-size distributions, with D_{50} less than 80 mm and negligible areal coverage by particles with intermediate axis diameters >130 mm. Median grain sizes are considerably coarser (>110 mm) for the set of four distributions (marked by red lines) from areas where evidence of spawning was absent despite apparently ideal hydraulic conditions. In these "unsuitable" facies, coverage by particles with intermediate axis diameters >130 mm ranges from 40 to 56%. The third set of four distributions (marked by yellow lines) is from the edges of active spawning areas and areas where marginal spawning and potentially failed redds were observed. These distributions therefore presumably characterize gravel near the threshold of spawning suitability. In three out of four, median grain size is between 85 and 105 mm. By themselves, these median grain sizes would not generally be expected to preclude spawning. But all of the distributions have coarse tails that overlap with the upper limits of the distributions from the "unsuitable" sites. This suggests that the spawning suitability may be especially sensitive to the abundance of excessively coarse material. Coverage by particles with intermediate axis diameters >130 mm ranges from 34 to 46% of the surface in these "threshold" areas. This offers corroborating support for the hypothesis that Sacramento River salmon are generally not able to successfully spawn in deposits where more than 40% of the surface is covered by particles with intermediate axis lengths bigger than 130 mm.

We suggest that the threshold should be loosely applicable to all of the river's Chinook salmon races; we expect that imprecision in facies-based, visual assessments of grain size are likely to be larger than race-to-race differences in the upper limits on particle size for spawning Sacramento River Chinook salmon.

3.2.3.7 Estimated versus measured values in facies mapping

We assessed errors in facies mapping using results from Wolman pebble counts that were conducted in select facies. Comparisons of estimated and measured values for median particle size, percent coverage by "immovable" particles, and percent occurrence of each qualifying substrate class are plotted in three separate panels in Figure 48. The diagonal lines on the plots mark perfect agreement between estimated and measured values. Estimates of D_{50} were systematically high (Figure 48A) but generally within ± 20% of the measured value. Estimated coverage by coarse particles was also systematically high, but the estimated-versus-measured discrepancy was generally less than ± 20% (Figure 48B). Discrepancies between estimated and measured coverage by individual substrate types are, with one exception, less than ± 10%, with data plotting more or less evenly around the line of perfect agreement, indicated no systematic bias in the estimates (Figure 48C). Discrepancies as big as those shown in Figure 48 are within acceptable limits, given the discrepancy between the spatial scales of the Wolman counts (which apply to 10 x 10 m, or 100 m^2, plots), and the facies maps (which apply to polygons with areas which in this case range from 273 to 46,188 m^2).

3.2.3.8 Synthesis of facies mapping results

Facies mapping results can be summarized as follows:

1. Our analysis at F1–F3 highlight the potential importance of gravel augmentation, bank erosion, and tributary inputs as offsetting factors for the systemic, dam-related deficit in coarse sediment supply.
2. Results from F2 highlight the importance local hydraulics on the presence/absence of suitable spawning gravel.
3. Results from F3 reveal the presence of redds in deposits that would be considered marginally suitable at best. This implies that virtually all suitable spawning gravel was in use by the fall run during the mapping (a necessary condition for saturation in 2006, 2005, and, by extrapolation, 1964; Figure 19; Table 10).
4. Results from F3 illustrate the potential for errors in mapping redds from the air; our field observations (from 2006) differ from what we mapped based on the 2005 helicopter survey, when fall run returns were similar in abundance (Figure 19; Table 10), and thus presumably utilized a similar total area of spawning.
5. Spawning area at F4 declined progressively over time to just one-third of the total area mapped in 1964. Areas that no longer support spawning are covered by a coarse, immovable bed. This provides clear support for hypothesis 1 and, by extension, is consistent with hypothesis 3 as well.
6. At Redding Riffle, progressive losses of spawning area have occurred despite repeated additions of gravel. The fact that spawning fish are now apparently unable to break through the surface of the bed suggests that it has become coarser over time in concert with the spawning area losses; the coarse, immovable deposits must be relatively new, given that Redding Riffle was once the site of some the river's most prolific Chinook salmon spawning. This is entirely consistent with hypothesis 1.
7. When considered together across all six facies mapping sites, our observations support the working hypothesis that fall run Chinook salmon of the Sacramento River are not generally able to successfully spawn in deposits where more than 40% of the surface is covered by particles bigger than the largest movable particle—assumed to be 130 mm in b-axis diameter.

3.3 Permeability and Spawning Gravel Quality

Permeability measurements are reported in Table 13 as the geometric means of the collection of measurements at each site and measurement depth. Data from individual measurements are available in the appendix. The mean permeability estimates are plotted against river mile in Figure 49, with separate panels for each drive depth. Error bars of data plotted in Figure 49 are estimated under the assumption that log-transformed permeability measurements from a given depth and location are normally distributed, with location-specific means and a universal (i.e., river-wide) variance for all drives at a given depth.

Table 13. Mean permeability estimates by location and depth.

RM	ID	Year	Before or after raking	Permeability (cm/hr)* by depth (in inches)				Number of samples by depth (in inches)			
				6	12	18	14	6	12	18	14
278.5	SW-7	2005	before	1946	227	32	–	5	5	3	0
278.5	SW-7	2005	after	5844	273	–	–	2	2	0	0
275.8	SW-8	2005	before	36	881	51	–	2	2	2	0
271.8	SW-6	2005	before	68	126	310	350	2	2	1	1
271.8	SW-6	2006	before	354	182	14	–	2	2	2	0
239.4	SW-2	2005	before	406	39	13	2210	3	2	2	1
239.4	SW-2	2006	before	508	1	11	–	2	2	2	0
236.8	SW-3	2005	before	3571	925	622	–	2	2	2	0
234.2	SW-4	2005	before	4971	3937	1493	–	3	3	3	0
228.2	SW-1	2005	before	3860	1	1	–	1	1	1	0
228.2	SW-1	2006	before	487	145	13	–	2	2	2	0
211.0	SW-5	2005	before	720	13	1	–	2	2	1	0
211.0	SW-5	2005	after	19480	2910	–	–	1	1	0	0
163.2	SW-9	2005	before	1415	558	523	–	3	3	3	0

*Reported permeabilities are geometric means. Data are not adjusted for temperature-dependent variability in viscosity, which is expected to be less than ± 5% from site to site in this study. To the extent that water temperatures differed from 10.6 ºC (51 ºF), which has a viscosity correction factor of 1.00, our results are not directly comparable with temperature-corrected permeabilities from other rivers.

3.3.1 Permeability by river mile

Statistical analysis confirms visual impressions from Figure 49—i.e., that there are no clear trends in permeability with river mile for any of the drive depths; regression statistics show a weak, statistically insignificant correlation (with r^2=0.25 and p = 0.17).

3.3.2 Estimates of the index of egg survival

The scaling of the right axes of Figure 49 is based on available data on survival-to-emergence and permeability (McCuddin 1977, Tagart 1976), which suggest that egg survival (S) of coho and Chinook salmon of the Pacific Northwest scales linearly with the log of permeability (P), as follows:

$$S = 0.1488 * \ln(P) - 0.8253 \quad (1)$$

when P is expressed in units of cm/hr.

The regression of equation (1) accounts for 85% of the observed variability in egg survival (Figure 50). To the extent that the regression of Figure 50 might differ from what we would observe for species-specific data from the Sacramento River, we expect that the survival index scaling of Figure 49 is only a semi-quantitative predictor of survival-to-emergence for the salmonids considered in this study. Even so, the fact that estimated survival indices for most of our locations fall well below the 25% level suggests they would generally be unsuitable for productive spawning due to low permeability. This appears to be especially true at sampling depths of 12 and 18 inches (Figure 49B and Figure 49C), in the range that Sacramento River Chinook salmon are generally observed to bury their eggs. This is consistent with hypothesis 3, under the assumption that permeability is regulated by the abundance of fine sediment in the subsurface. Yet hypothesis 3 would only be supported by these observations if the low permeabilities applied specifically to the upper river, where coarsening has reduced bed mobility. This is not the case. Rather, permeability shows no clear trends with river mile, implying that it is no better or worse in the upper river relative to conditions farther downstream. Hence, support for hypothesis 3 is lacking.

The fact that estimated survival indices were universally low was surprising, given that all of our permeability sites were close to zones of active spawning. The apparent discrepancy between observed spawning use and estimated gravel quality could be explained by one or more of the following:

- gravel quality is low and the spawning fish we observed were building redds that would support low survival-to-emergence levels,
- the relationship between survival index and permeability for Sacramento River Chinook salmon is different from the one expressed in Equation 1 (which is fit to multispecies data from the Pacific Northwest), or
- redd building enhances permeability enough to make the sites suitable for successful spawning.

There is some indication that the third possibility may be important, based on observations of improved permeability at several sites where we attempted to simulate redd construction manually.

3.3.3 Effects of "redd-building"

In our provisional test of whether redd-building has a significant effect on permeability at depth, we observed mixed results. In two cases of redd-building (simulated manually in this study with a McCloud rake), permeability at the 6-inch depth was much higher after raking than before. In the third case, it was unchanged. That "redd-building" had little effect on permeability in the third case may be due to any number of factors, including unfavorable hydraulic conditions (i.e., with flow too slow to carry the fines away), or insufficiently vigorous disruption of the bed. It may alternatively reflect an initial absence of interstices-clogging fines; without many fine particles to begin with, the raking experiment would not have a large effect on measured permeability.

Effects of "redd-building" on permeability at the 12-inch depth were even less clear. At one of the sites, measured permeability at 12 inches was much higher after raking than before. At the other two sites, changes in permeability at 12 inches were not detectable at any conventional level of statistical significance. This may simply reflect a failure to rake to the desired depth. Raking depth was difficult to measure precisely due to irregularities of the initial surface. The lack of change in permeability at depth may alternatively reflect the fact that the bed was not disturbed vigorously enough for entrainment of fine material into the flow. In any case, given the difficulties inherent in simulating redd-building by female salmonids, we suggest that our observations of dramatically increased permeability at some of the sites reflects the potential for improved conditions for egg pockets at depth in the aftermath of spawning. It also corroborates indications from Figure 49 that gravel cleaning via redd-building would be necessary for productive spawning at our permeability sites on the Sacramento River.

3.3.4 Permeability by depth

Our results indicate that permeability is higher at 6 inches than it is at the other measurement depths. Permeability was greater at 6 inches than at 12 inches in 20 of 25 samples (excluding the "before" and "after" measurements at raking sites). Under the null hypothesis that permeability is insensitive to depth, such that it would be greater at 6 inches than at 12 inches half the time, the probability of seeing greater permeability at 6 inches 20 or more times in 25 trials is approximately 0.002. This falls well within the typically accepted confidence limits for statistical significance. Conversely, permeability at 12 inches was greater than it was at 18 inches in just 13 of 24 samples; this is not different from the null hypothesis (i.e., that depth doesn't matter) at any reasonable confidence level ($p=0.42$). Taken together for the river as a whole, the permeability results indicate that the upper 6 inches or so of the bed is significantly more permeable than it is at depth.

If we assume that permeability is inversely related to the concentration of fine sediment in the subsurface, our permeability versus depth results imply that the upper framework of the bed has remained relatively free of fine material, compared to material at depth, despite decades of low-level inputs of fine material and a reduced frequency of flushing flows (caused by coarsening in the upper river and changes in the magnitude-frequency relationship of flow for the river as a whole). For salmonids, this means that entombment and suffocation associated with infiltration of fine material into clean, newly built redds is unlikely to be significant over the course of a single, several-month-long, spawning-to-emergence period. In other words, if rates of fine sediment infiltration were high (and thus posed a threat of entombment and/or suffocation), we would expect to see that the upper 6 inches of gravel would be impacted with fine sediment, given the decrease in bed mobility implied by coarsening in the river. These results are contrary to hypothesis 3.

3.3.5 Year-to-year variations

We measured permeability in both the fall of 2005 and the fall of 2006 at three sites: SW-1, SW-2, and SW-6. We were unable, however, to make any statistical comparisons of year-to-year variations in permeability, due to high site-to-site variability in permeability and limited number of samples in each case.

3.3.6 Synthesis of permeability results

Permeability results can be summarized as follows:

- Permeability is higher at 6 inches than it is at the other measurement depths across all sites spanning the upper and middle river. For salmonids, this means that entombment and suffocation associated with infiltration of fine material into clean, newly built redds is unlikely to be significant over the course of a single, several-month-long, spawning-to-emergence period. This contradicts hypothesis 3, which states, in part, that gravel quality has declined due to increased concentrations of fine sediment in the subsurface.
- Estimated survival indices of our sites are almost universally poor. This would generally support hypothesis 3, if it applied specifically to the upper river, where coarsening has reduced bed mobility. Yet permeability shows no clear trends with river mile, implying that it is no better or worse, on average, in the upper river.

In general, the permeability data provide inconclusive tests of the study hypotheses, due to the wide spatial variability in permeability and the lack of data on historical conditions.

3.4 Bed Scour

Scour chains and boxes were installed at six sites in mid December 2005. The sites were reoccupied for monitoring in late October 2006, when daily average discharges were similar to those that occurred during installation (Table 14). This helped make reoccupation of scour chain sites relatively straightforward, because water levels were similar in each case. It also made big changes (which did occur at 2 of the sites) very obvious. If water levels had instead been higher, due to higher flows for example, then many of the sites would have been inaccessible due to unsafe wading conditions. It turned out that two of the sites actually were unsafe for wading, but this was not because flow was different, but instead because the river had shifted laterally such that deep water was flowing over the scour chain sites during the monitoring phase.

Table 14. Daily average discharge near scour chain sites.

Location	Date of installation	Date of monitoring	Discharge during installation (cfs)	Discharge during monitoring (cfs)
Sacramento River at Keswick (RM 302)	12/14/2005	10/25/2006	5060	5450
	12/15/2005	10/26/2006	5060	5700
	12/16/2005	10/27/2006	5070	5650
Sacramento River at Bend Bridge (RM 258)	12/14/2005	10/25/2006	6470	6580
	12/15/2005	10/26/2006	6450	6510
	12/16/2005	10/27/2006	6430	6600
Sacramento River at Colusa (RM 143)	12/14/2005	10/25/2006	6300	5290
	12/15/2005	10/26/2006	6230	5250
	12/16/2005	10/27/2006	6150	4950

3.4.1 RM 273.0

At SW-10 (a Wolman count site; Table 3), three scour chains and three scour boxes were installed on 12/14/2005 at the waters edge. SW-10 is immediately across from Cottonwood Creek, at RM 273.5. On 10/26/2006, reoccupation of survey points on the bank revealed that the water's edge had migrated laterally by at least 24 m, whereas the thalweg had shifted course such that it was almost directly in line with the scour chains. Conditions near the nest of chains were unsafe for wading, and we suspect that the chains have been completely uprooted by at least a meter of scour (Table 15). The scour boxes are also presumably gone; we suspect the bar surface has been eroded away as the brunt of the river's flow has shifted over it.

Table 15. Scour observations from the upper and middle Sacramento River, 2005–2006.

Location	River Mile	Monitoring period	# chains installed	# chains found	Estimated scour (cm)	Estimated deposition (cm)	Notes
SW-10	273.0	12/14/2005 to 10/26/2006	3	0	>100	0	migration of the bank was >24 m
SW-6	271.7	12/14/2005 to 10/26/2006	0	–	0	0	only scour boxes were installed; remnants of paint on rocks suggests that scour has been minimal
SW-11	246.2	12/16/2006 to 10/25/2006	4	4	-5–4 *	3–8.5 *	
SW-2	239.6	12/15/2006 to 10/26/2006	4	4	-4–6 *	3–7 *	
SW-3	236.8	12/15/2006 to 10/26/2006	4	0	>150	0	migration of bank was >100 m
SW-1	228.2	12/15/2006 to 10/26/2006	4	0	~100	0	bank erosion was minimal here, but a scour hole developed where the chains were installed and scour boxes are gone with no trace

*Measurement uncertainties are probably ± 5 cm. This implies essentially no scour or deposition at the sites.

3.4.2 RM 271.7

No chains were installed at SW-6 (RM 271.7) because the surface armor was too coarse to penetrate with the scour chain installation device. Nevertheless, we installed three scour boxes 20 m apart along the bank at the site—extending from the head of the riffle to a point 40 m downstream. As of 10/26/2006, there were still traces of paint on particles in each of the scour boxes at SW-6. This implies that there has been minimal disruption of the surface at the site, despite the fact that several post-installation flood pulses were marked by flows at Keswick (RM 302) and Bend Bridge (RM 258) (the two USGS gauges that bracket the site) that were more than five times higher than they were at installation (Figure 12). The fact that only traces of paint remain on each rock (Figure 51) indicates that paint had been abraded away and that remote observations of the boxes (e.g., from CDFG airplanes) would have been problematic (given that the paint patches were only visible from careful, on-site inspection). We noted traces of paint on two rocks that had been displaced from the lowest patch. In one case, a 90 x 140 x 180 mm stone had traveled 8.8 m, and in the other, a 50 x 150 x 160 mm stone traveled 18.9 m. It is not clear whether these displaced stones were moved by flow or the anglers known to frequent the popular fishing hole that lies just downstream, near Battle Creek.

3.4.3 RM 246.2 and RM 239.6

The scour chains at SW-11 (RM 246.2) and SW-2 (RM 239.6) were found with protruding lengths that were essentially equal to what they were immediately after installation. This is consistent with little or no change in bed-surface elevation locally, and implies there has been essentially no scour or deposition at the sites (Table 15). The fact that flow at each site was essentially the same during installation and monitoring (Table 14, Figure 12) and that the chains were near the water's edge in each case are further indications of minimal morphological change at the sites. This seems remarkable given that mainstem flow at nearby Bend Bridge (RM 258) remained above 60,000 cfs for more than 14 days and peaked at 88,100 cfs in the intervening period (Figure 12). No scour boxes were installed at SW-11 because they would have been very conspicuous, due to a clear line of sight from Interstate 5. Scour boxes painted at SW-2 in 2005 were missing as of 10/26/2006, implying there was some localized disruption of the bar surface in the vicinity of the scour boxes, despite the evidence of broad-scale stability and lack of scour from the scour chains. The possibility of vandalism of the boxes at SW-2 cannot be ruled out.

3.4.4 RM 236.8

Significant point bar erosion occurred in WY 2006 at SW-3 (RM 236.8). Two of our survey points, which, in 2005, had been 80 and 100 m from the water's edge, were completely submerged as of 10/26/2006 (Figure 52). This implies that the bank migrated more than 100 m after the chains were installed. Fresh-looking erosion scarps in the 3 m tall banks upstream of the bar are further evidence of recent morphological change locally. Measurements indicate water depth is greater than 3 m at the approximate site of the chains, implying >1.5 m of scour there, and indicating that the chains (which were only 1 m long) have been completely excavated by the flow.

3.4.5 RM 228.2

Scour at SW-1 (RM 228) was also evident but to a much lesser extent than it is at SW-3. As of 10/26/200, a scour hole had developed over the site of the chains, but lateral bank erosion had been minimal. We guessed that the chains were gone, but we were unable to verify this due to unsafe wading conditions. The fact that wading had become unsafe since installation, even though discharge was similar during installation and monitoring, indicates that scour had been significant at the site. Based on the change in position of riffle head from installation to monitoring, we estimate that downstream migration of the gravel bar was about 30 m over the observation interval. The scour boxes from SW-1 are gone without a trace, implying that the bed surface was disrupted by flows in the intervening period.

3.4.6 Synthesis of scour observations

The pattern of scour and stability implied by the scour chains and boxes is broadly consistent with the upper river's reputation for exhibiting fossilized morphology and the middle river's reputation for mobility and change. The exceptions, including the unstable site across from Cottonwood Creek (SW-10, in the upper river) and the stable site immediately below Red Bluff (SW-2, in the middle river), are moreover consistent with local variations that would tend to overwhelm any broader tendencies toward stability or mobility. Cottonwood Creek is a major sediment source (Table 8), so it is not altogether surprising that the point bar immediately across from it is dynamic, even when the relative stability of the surrounding upper river as a whole is taken into account. Conversely, although the stable site below Red Bluff is technically within the middle river, there are not any major sediment sources upstream (owing to the absence of local bank erosion and tributaries) and the site is close to Lake Red Bluff (RM 243) where the river's energy slope (and propensity for change) is locally reduced. This would tend to produce a stable morphology, as observed in this case, despite the site's setting within the typically dynamic middle river.

In summary, the pattern of scour and stability observed here is one of little surface mobility at sites where external sources of sediment supply are locally absent, and conversely more significant scour and lateral change at sites where sediment supply and the observed frequency of morphologic change are relatively high. Although this does not clearly bear on any of the study hypotheses, it confirms the importance of taking the effects of local sediment sources into account in the assessment of spawning area changes over time. It also suggests that scour can be significant enough (>1 m; Table 15) in the middle river to excavate redds, killing eggs and alevin if scouring flows occur during incubation. This could affect the fall run (the only race to use the scour-prone middle river for spawning) because they emerge in early winter when flows are periodically high enough to mobilize the bed.

3.5 Sediment Transport Modeling

TUGS model simulates changes in grain size of the river by accounting for how its sediment flux interacts with sediment in both the surface and subsurface of the channel bed. We modeled sediment transport from RM 302 to RM 290, where available data are sufficient to simulate how spawning gravel is likely to have changed over time due to sediment transport and the evolution of sediment sizes in the surface and subsurface.

3.5.1 Changes in storage

TUGS modeling yields several types of output. For example, it can predict how in-stream sediment storage has changed, by simulating how sediment is routed from reach to reach over time (Cui in press, Cui 2007). Results from reach 3 predict that in-stream sediment storage should decrease progressively, in years with high flows, due to the cessation of sediment supply from upstream sources (Figure 53). By 1990 the cumulative post-dam deficit in sediment storage between RM 295 and RM 290 was close to 80,000 m^3 (105,000 cubic yards). Gravel injections in 1990 and again in 2000 led to substantial increases in sediment storage in the reach, but were concentrated at the downstream end (near RM 290), and thus had little effect on storage throughout much of the reach.

3.5.2 Changes in grain size

TUGS model also permits simulation of the evolution of grain size over time, beginning with known or assumed initial conditions (Cui in press, Cui 2007). At Redding Riffle (RM 297.7), for example, the model predicts that, after an initially sharp increase, median grain size of the surface should increase progressively, during years with high flows (Figure 54). TUGS simulations also predict that augmentation-related decreases in grain size would have been quickly reversed at Redding Riffle (Figure 54). Much of the coarsening and subsequent loss of augmented gravel at Redding Riffle appears to have been caused by upstream propagating effects of the mining pit at Turtle Bay, which was excavated in the 1940s to provide material for Shasta Dam construction. Further downstream, between RM 291.4 and RM 295, coarsening is more gradual, but nevertheless continuous, suggesting that further increases in grain size are inevitable (Figure 54).

3.5.3 Changes in bed mobility

Another instructive output of TUGS model simulations is the relationship between sediment transport rate and flow (i.e., the sediment rating curve for flow) at any given time as the surface evolves. For the Sacramento River simulations, the predicted bedload-rating curve for RM 294 is shown to shift over time (Figure 55), such that the sediment transport rate for a given flow has been decreasing progressively since the dams were constructed. The family of curves shown in Figure 55 reflects a decrease in the mobility of the surface over time; as the surface has become increasingly coarse (Figure 54), the sediment transport rate at any given flow has been reduced accordingly, due to an decrease in the prevalence of material that would move at relatively low flows. A particularly pronounced shift in the rating curve is predicted to have occurred in the wake of a large flood in 1939 (Figure 55), which presumably exported a large volume of sediment without replacement (due to the effects of the mining pit at Turtle Bay, just upstream).

3.5.4 Changes in bed-surface elevation

TUGS simulations also generate predicted changes in bed elevation. These are plotted in Figure 56 for several points in time over the simulated period of record on the upper Sacramento River. Several observations from Figure 56 are worth noting:

1. The initial condition at the Turtle Bay mining pit is a deep hole capable of capturing virtually any sediment in transit from upstream. The pit generates an upstream-propagating pulse of incision that reduces bed elevations. Key unknowns are (i) the initial depth of the mining pit and (ii) the local depth of bedrock, which together set limits on the depth of incision upstream. The actual depth of incision is therefore unknown. Our simulations show that it could easily degrade the channel by several meters in the immediate upstream vicinity of the pit. The incision zone encompasses Redding Riffle, implying that some of the coarsening at the site can be attributed to upstream-propagating effects of in-stream mining at Turtle Bay.
2. Increases in bed elevation are predicted above RM 299, due to grade control by ACID dam and the large augmentation volumes within the reach at Salt Creek and Keswick Dam (Figure 18).
3. Decreases in bed elevation occur throughout the reach below Turtle Bay, due to the system-wide shutdown in sediment supply. A pronounced increase in elevation occurs in the most recent interval near RM 290, due to the simulated effects of gravel augmentation at the Tobiasson (RM 291.6) and Shea Levee (RM 290) injection sites (Figure 18).
4. Changes in bed elevation predicted by TUGS are generally small (i.e., typically less than 0.5 m) relative to the natural, year-to-year variability in bed elevations we would expect on a river as deep and wide as the Sacramento River. We suggest that a comparison of historical cross sections would be an insensitive indicator of dam-related changes in bed elevations over time.

3.5.5 Predicted and observed values of median grain size

One caveat of sediment transport modeling is that the predicted D_{50} values are cross-sectional averages. We know that individual cross sections of the Sacramento River harbor considerable spatial heterogeneity in grain size, as illustrated clearly in each of the facies maps (Figure 41–Figure 45). This means that cross-sectional averages predicted by TUGS model will generally be incompatible with point measurements of grain size from Wolman counts and bulk samples. The lack of compatibility between what we can predict and what we can measure makes it difficult to determine whether TUGS model yields realistic estimates of grain size. One option would be to compare site-specific grain sizes from TUGS with reach-averaged estimates generated from the facies maps. But this would be inconclusive because there are over 12 river miles of modeled grain sizes and only 5 short facies mapping sites for the comparison. To work around the problem, we compared TUGS results with Wolman count data for the upper river as a whole, rather than on an individual case-by-case basis. Our analysis shows that simulated D_{50} values fall within the wide envelop defined by results from Wolman pebble counts (Figure 57). The general agreement between simulated and measured grain sizes is about as close as should be expected, given that the modeling generates cross-sectional averages, rather than point measurements, and given the lack of initial information on grain size, sediment supply, and bed surface elevation for the pre-dam Sacramento River.

3.5.6 Benefits of gravel augmentation

TUGS model suggests that the benefits of gravel augmentation on the upper Sacramento River (Figure 18) should have been noticeable, but may be ephemeral and localized, in part because the total volume of augmented gravel (at just over 187,000 m^3 or ~250,000 yd^3) is much smaller (by a factor of 14) than the cumulative deficit of coarse sediment supply from above RM 302 (equal to about 2.3 million m^3 or 3 million yd^3; see section 1 for references). For example, TUGS modeling of the reach encompassing facies sites 1 (Figure 41) and 3 (Figure 43) suggests that there has been a temporary, partial recovery of sediment storage (Figure 53) in response to small additions of gravel (Figure 18) in the downstream end of the reach. This is broadly consistent with observations from the facies mapping work.

In general, we expect that gravel additions are manifested in an increase in gravel depth and/or area along spawning habitat margins. Yet we further expect that benefits of gravel augmentation should be ephemeral, because subsequent flows should continue to disperse sediment downstream. Observations of broad areas of spawning-sized gravels in hydraulically unsuitable locations (CDWR 1995) lend support for these expectations.

TUGS confirms that added gravel may had particularly ephemeral benefits at Redding Riffle (Figure 54), which appears to suffer from upstream-propagating effects of in-stream mining at Turtle Bay. Most of the coarsening and subsequent loss of augmented gravel at the riffle has been caused by the mine-related drop in baselevel, according to TUGS model.

In general, the volume and frequency of gravel augmentation should be sufficient to strike a balance with losses due to the systemic coarse sediment supply deficit. Such a balance would be manifested locally as a "dynamic equilibrium" of spawning gravel, with spawning area remaining roughly constant over time, even as its spatial distribution shifts in response to local changes in hydraulics and sediment dynamics. There is some indication that such a condition may be developing locally at two of our facies mapping sites (see Figure 41 and Figure 43). Results from additional simulations of the TUGS model should help shed light on how much manually added gravel will be needed to offset the ever-growing losses of the upper Sacramento River as a whole (Stillwater Sciences, in preparation).

3.5.7 Synthesis of sediment transport results

Results from TUGS sediment transport modeling of the upper Sacramento River are broadly consistent with hypothesis 1—that the bed has been coarsening progressively over time, and hypothesis 2—that coarsening has propagated downstream progressively over time. For example, predicted median grain sizes increase sharply, by 80% within the first 20 years of the simulation at Redding Riffle, due to upstream-propagating effects of in-stream mining at Turtle Bay and downstream-propagating effects of reduced sediment supply from the dams (Figure 54). Farther downstream, between RM 295 and RM 290, coarsening is more gradual but nevertheless continuous (Figure 54), suggesting that grain size will probably continue to increase over time. The decrease in sediment storage in reach 3 (Figure 53) reflects transport by successive high flows and the absence of supply from coarse sediment sources; because transport is generally dominated by selective removal of relatively fine material, an absence of supply tends to cause progressive coarsening with each successive bed-mobilizing event. The predicted shift in the sediment rating curve for RM 294 (Figure 55) is a direct result of coarsening; as grain sizes increase, bed mobility drops, reducing the amount of sediment carried by a flow of a given magnitude. This has implications for hypothesis 3, to the extent that a less mobile bed is generally prone to increases in fine sediment concentrations in the subsurface. Figure 55 provides perhaps the most straightforward display of how bed mobility has changed over time, according to TUGS model.

The key results of the sediment transport modeling are insensitive to initial conditions. For example, the deep mining pit at Turtle Bay imposes a base-level drop that degrades Redding Riffle (Figure 54), irrespective of both the size of the pit and the initial grain size in the reach. Moreover, coarsening occurs in all reaches that have been deprived of sediment supply, irrespective of initial grain size; coarsening is an inevitable consequence of sediment transport in the absence of supply.

Results from sediment transport modeling are largely inconclusive about whether fine sediment concentrations in the bed are increasing (hypothesis 3), because rates of fine sediment supply are not well constrained along the river. For reliable estimates about changes in the level of fine sediment in spawning gravel, TUGS would need rates of fine sediment inputs from bank erosion and agricultural runoff (from both diffuse and point sources). Ideally the data would span multiple years and would be broken up into piecewise contributions by river mile. In the absence of such data, results from TUGS are unable to definitively support or contradict hypothesis 3.

4 ASSESSMENT OF STUDY HYPOTHESES

Results from the gravel study allow us to reassess our working hypotheses about changes in spawning gravel over time on the Sacramento River., We can then revise, as necessary, our conceptual model of:

- how bed sediment has changed over time in the upper and middle reaches of the river,
- how the observed changes in bed sediment are likely to have affected spawning salmonids, and
- how the system is likely to change in the absence of remedial measures.

4.1 Hypothesis 1: Bed Coarsening over Time

Hypothesis 1 is that progressive coarsening of the bed surface since 1980 has continued to reduce the extent of suitable salmonid spawning habitat between ACID Dam (RM 298.4) and Anderson Bridge (RM 283.3). Our assessment of this hypothesis was informed by (i) our time-series analyses of spawning area for the river as a whole, (ii) our analysis at select sites of how the distribution of redds corresponds with the distribution of sediment size on the surface, (iii) our time-series analysis of grain size distributions for the river as a whole (from the statistical analysis of the Wolman counts), (iv) the observed patterns of bed mobility and scour, and (v) our sediment transport modeling results.

For hypothesis 1 to be reasonable, there should be evidence of coarsening in the reach upstream of Anderson Bridge (RM 283.3) since 1980. Our evidence for hypothesis 1 can be summarized as follows:

- Facies mapping indicates there has been a progressive loss in spawning habitat within at least two key winter-run spawning sites—a bend at RM 292.7 (Figure 44) and Redding Riffle (Figure 45), the historical locus of some of the river's most prolific Chinook salmon spawning. The results indicate that the bed has become immovably coarse in areas that once supported fall run redd construction. Hence spawning area losses at the sites are consistent with what we would expect to see if the systemic, dam-related sediment supply deficit has led to coarsening in the reach bounded by RM 292 and RM 298.
- After supporting few redds in 1964 and 1980, the reach between Keswick Dam (RM 302) and ACID (RM 298.5) now supports channel-spanning spawning dunes during the peak of fall run spawning. This appears to be an effect of gravel augmentation in the reach, at the Keswick Dam and Salt Creek injection sites. Losses in spawning area at Redding Riffle, just downstream of ACID, have been substantial but have nevertheless been mitigated somewhat by the effects of gravel augmentation. Our statistical analysis of changes in grain size over time suggests that benefits of gravel augmentation are largely absent downstream of RM 298. This is probably due to the disruption of sediment transport continuity at Turtle Bay (RM 296), a large in-stream mining pit which apparently intercepts and traps much of the added gravel before it can be delivered downstream.
- When considered in an average sense, over the scale of multiple river miles, grain size measurements indicate that the surfaces of gravel deposits have been progressively depleted of relatively fine material (Figure 40; Table 11), leading to a net coarsening of the surface since at least as early as 1980 in the reach between RM 298 and RM 280. This implies that there has been coarsening over time in the reach. Grain-size data from individual sites are generally less conclusive about coarsening, due to high natural variability in grain size over the 10- to 100-m scale of individual bars and bedforms.
- TUGS simulations predict nearly continuous post-dam coarsening in the upper river, with short-lived, localized reversals (towards finer grain sizes), due to simulated effects of gravel augmentation. Direct field observations from the facies mapping and spawning surveys generally confirm that gravel augmentation projects have led to noticeable, but possibly short-lived, gains in spawning habitat immediately downstream of the injection sites (i.e., at Redding Riffle [Figure 45] and RM 2.7 [Figure 43]). The offsetting effects of small additions of gravel from tributaries and bank erosion sites are also evident in our analysis of spawning area (Figure 17) and in the facies mapping (Figure 41).

When effects of potentially confounding sources of coarse sediment and other factors are taken into account, the balance of evidence supports hypothesis 1. The evidence is particularly strong for the reach bounded by RM 292 and RM 298, thanks to observations from the facies mapping work.

4.2 Hypothesis 2: Progressive Downstream Migration of Bed Coarsening

A reduction in sediment supply due to a dam (or any other factor for that matter) should affect the reach immediately downstream of the deficit first. Once sediment transport has locally exhausted any in-channel sediment storage in that reach, the deficit in supply should then propagate to the next reach downstream. This mechanism for downstream propagation of sediment supply deficits leads to hypothesis 2—that bed coarsening on the Sacramento River is working its way progressively downstream over time. CDWR (1980) speculated that the coarsening had affected the upper Sacramento River from Keswick Dam (RM 302) to at least as far downstream as Anderson Bridge (RM 283.3), based on their analysis of changes in spawning area over time. If hypothesis 2 is correct, then we should expect to see that coarsening has now progressed farther downstream, to below Anderson Bridge (RM 283.3).

Grain size data from individual sites within the reach are inconclusive about whether coarsening is occurring and propagating downstream (Figure 23, Figure 24, Figure 32, and Figure 33), due to the potentially confounding effects of spatial variability in grain size on sampled point bars. Moreover, our statistical analysis of the Wolman count data indicates that deposits have been progressively depleted of their fine and medium gravel over time (Figure 37; Table 11), suggesting that coarsening is a broad-scale phenomenon that has been affecting the upper river as a whole (above RM 280) since at least as far back as 1980, without any clear evidence for the downstream propagation suggested by hypothesis 2.

On the basis of the grain-size data alone, we cannot rule out the possibility that coarsening may have commenced throughout the upper river by 1978, when the first samples were collected. Indications from sediment transport modeling are also inconclusive about this. On the one hand, TUGS model predicts substantial dam-related increases in grain size as far downstream as RM 291 by the end of the simulations (Figure 54). This implies that coarsening probably migrated significantly further downstream, perhaps as far as Cottonwood Creek, or even beyond. On the other hand, we were unable to model the downstream propagation of bed coarsening because we could not effectively quantify the timing and volume of in-stream mining and tributary inputs below RM 290. Taken together, these considerations suggest that the available grain size data and sediment transport modeling provide for an inconclusive test of hypothesis 2.

Documenting whether coarsening is propagating downstream over time is important for understanding potential threats to all of the Sacramento River's Chinook salmon. It is especially critical for management of the fall run. Fall-run Chinook salmon currently spawn along a much longer stretch of river below the dam relative to the other races. If bed coarsening is propagating downstream of Cottonwood Creek, then it will probably have especially significant effects on fall-run Chinook salmon.

As noted above, spawning area in the reaches below RM 273.5 appears to have remained stable from 1964 to 1980 (Figure 17). This makes sense, given the relatively high rates of sediment supply from Cottonwood Creek (Table 8). It is also consistent with our scour box observations at RM 271.7, which indicate that the surface remained stable during WY 2006 (Table 15). Yet the fact that there were prolonged flows above ~60,000 cfs during the scour box monitoring period (Figure 12) implies a remarkable lack of mobility that may reflect either:

- a locally low transport capacity (associated with local channel slope, for example), which would tend to support a stable distribution of spawning area over time; or
- the fact that a wave of coarsening has already swept through the reach, leaving a surface of increased armoring and immobility.

The latter alternative would help explain why the bed's armor at RM 271.7 was impossible to penetrate with our scour chains. Coarsening below Cottonwood Creek would be difficult to reconcile with the apparent local stability of spawning area in recent surveys, and with indications from our grain size analysis (Table 11), that coarsening has been most pronounced in recent years, in the upper river from RM 280 to RM 298.

For hypothesis 2 to be reasonable, there should be evidence indicating that coarsening has progressed downstream from Anderson Bridge (RM 283.3) since 1980. When considered together, over the scale of multiple river miles, the time series of grain-size data suggest that coarsening may have been affecting the entire upper river to at least as far downstream as Cow Creek (RM 280) since at least 1980, without any clear evidence for the downstream propagation suggested by hypothesis 2. This is corroborated by sediment transport modeling, which shows that coarsening can propagate downstream rapidly, and may have started affecting the entire upper river before the first grain size samples were collected in 1978.

Taken together, the balance of evidence does not support hypothesis 2. An important qualifier is that the time series of grain-size data provide for an inconclusive test of whether coarsening may have propagated progressively downstream before 1980 (because no pre-1980 data are available). Another noteworthy qualifier is that grain size data from individual sites provide an inconclusive test of the hypothesis, due to high natural variability in grain size and uncertainties associated with reoccupying previous sampling sites.

4.3 Hypothesis 3: Increase in Fine Sediment in Subsurface Bed Material

Hypothesis 3 states that the quality of any remaining spawning gravel in the upper river has declined in concert with the river's ability to flush fine sediment from the subsurface of the bed due to reduced mobility associated with (i) coarsening of the surface and (ii) a reduced frequency and magnitude of peak winter floods. To help identify whether hypothesis 3 is reasonable, we investigated:

1. whether bed-surface mobility has changed significantly over time, and
2. whether fine sediment concentrations in the subsurface of the bed have increased over time.

4.3.1 Changes in bed-surface mobility

We already discussed in section 1.3.2 how flow regulation on the Sacramento River has led to substantial changes in the magnitude-frequency relationship of flow. In particular, the post-dam reduction in $Q_{1.5}$, has been estimated to be about 30% downstream of Keswick Dam (Kondolf et al. 2000), implying that the recurrence intervals of surface-mobilizing discharges have increased substantially in the post-dam era.

Another key regulator of bed mobility, besides the magnitude-frequency relationship of flow, is the grain-size distribution of the bed surface, which helps regulate how much sediment will be moved during a flow of a given magnitude. Mobilization rates are prone to change because they depend on a number of factors, including the grain-size distribution of the bed and local channel geometry (i.e., width, depth, and slope), which modulates the shear stress exerted on the bed under a given flow. These factors are generally thought to be sensitive to sediment loading, which the dams have altered substantially in the upper river. Consequently, it's important to consider whether human impacts on the system have led to substantial changes in the factors that regulate mobilization rates.

In general, bed surfaces with coarser distributions will be prone to less sediment transport (and thus will be "less mobile"), although other factors can be important[4]. As we have already seen, the balance of evidence indicates that the bed surface has coarsened substantially since the dams were constructed in the 1940s (i.e., as proposed in hypothesis 1). This implies that the bed mobilization rates in the upper river have decreased. Our statistical analysis of the grain size data suggest that the extent of coarsening has progressed at least as far downstream as Anderson Bridge (Table 11; Figure 40), and maybe even as far as Cottonwood Creek (based on scour box results and pronounced armoring at one site). Hence, the time-series of grain size data implies that the bed of at least part of the upper river (i.e., from RM 298 to RM 280) has become less mobile over time.

Were changes in channel geometry also significant enough to affect mobilization rates? A dam-related reduction in sediment loading would generally be expected to promote incision and narrowing, which would generate steeper slopes capable of carrying coarser sediment. This would effectively reduce the mobilization threshold and thus increase the frequency of mobilization, all else equal. Yet widespread incision and narrowing has not been observed on the upper Sacramento River (e.g., CDWR 1980). Historical planform maps instead indicate that channel margins have been static, except in the immediate downstream vicinity of tributaries (CDWR 1980). Sediment transport modeling predicts minimal changes in bed surface elevations, except in the immediate vicinity of Turtle Bay (Figure 56), due to the anomalously deep in-stream mining pit there. In the one other case were evidence of a steepened channel has been documented, near Clear Creek, it was also attributed to local degradation associated with in-stream mining (Gomez 1974, as cited in CDWR 1980), rather than the dam-related reduction in coarse sediment supply. Available evidence confirms that the channel has more or less maintained its historical shape and bed elevations, despite the marked overall reduction in coarse sediment supply due to the dams. The lack of incision and migration in the upper river can be explained, at least in part, by the fact that it is bounded both laterally and vertically by erosion-resistant bedrock (CDWR 1980).

The threshold for complete mobilization (i.e., scour) of the surface is difficult to estimate quantitatively, in part because it varies considerably depending on local channel geometry. At Redding Riffle, the scour threshold of loosely placed spawning gravel was estimated to be between 36,000 and 50,000 cfs, based on observations of manually augmented gravel during subsequent flood stages (Parfitt and Buer 1981). In the vicinity of RM 302, the pre-dam threshold for surface scour is estimated to be roughly 40,000 cfs, based on sediment transport modeling. The surface coarsening associated with reductions in sediment supply may have increased the threshold by a factor of two, according to our simulations. Farther downstream, at RM 271.7, our observations of undisrupted scour boxes for WY 2006 imply a local threshold of >80,000 cfs for scour of the surface, based on flows at the Bend Bridge gauge (Table 15, Figure 12), 14 river miles downstream.

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[4] For example, if the bed's grain-size distribution is bimodal, with an abundance of both coarse and fine material, its transport rates might be relatively low, given the amount of fine material, due to wake effects, in which large particles shield fine material from the brunt of the flow.

Irrespective of their precise values at any given point along the upper river, it seems clear that the threshold for surface scour has increased progressively as the frequency of high, bed-mobilizing flows has been reduced by the operations of the Shasta, Keswick, and Whiskeytown dams. The bed mobility changes of the upper Sacramento River have important implications for whether flows are able flush fine sediment out of the bed often enough to keep gravel suitable for spawning by Chinook salmon.

4.3.2 Changes in fine sediment concentrations

Whereas the balance of evidence supports the hypothesis that there has been a substantial reduction in bed mobility (due to coarsening of the surface), there is no indication that the mobility of sand and silt has been substantially reduced by the installation of the dams. Flows are generally high enough, and critical shear stresses are low enough, that we can reasonably expect that sand and finer particles are effectively transported along the bed surface during all but the lowest flows, much as they probably were in the pre-dam era. On the other hand, the dams have undoubtedly reduced the *supply* of sand and silt, particularly for reaches immediately downstream. Recruitment of fine sediment is now limited to inputs from tributaries (Table 8), agricultural runoff, and bank erosion—which is not widespread in the upper river (CDWR 1980). Yet even a small amount of sand traveling on the bed could, over time, lead to excessive accumulations in the subsurface (as saltating grains are progressively incorporated into the bed). This would tend to reduce spawning gravel quality if the bed is not mobilized frequently enough to flush out the collected fines. Hence it is important to determine whether there have been any significant changes in fine sediment concentrations in the bed of the upper river.

We have two sources of data for an assessment of changes in fine sediment concentrations over time: bulk samples and permeability measurements. However, we were able to make a time series comparison of only 2 bulk sediment samples from the upper river (Figure 23 and Figure 24). While it contradicts hypothesis 3, by suggesting a decrease in fine sediment concentrations in the bed from 1995 to 2005, the extent to which it reflects a system-wide trend for the upper river as a whole (as opposed to a strictly local phenomenon) is impossible to determine.

Our permeability data is similarly inconclusive about how fine sediment concentrations in the subsurface have changed over time, in large part because baseline data on historical conditions are not available; our permeability study is the first of its kind for the upper Sacramento River. Nevertheless, our measured permeability measurements imply universally poor survival indices (Figure 49). This would seem to support hypothesis 3, assuming that permeability is regulated by the abundance of fine sediment in the subsurface, but only if the low permeability values applied specifically to the upper river, where coarsening has reduced bed mobility. Permeability shows no clear trends with river mile, implying that it is no better or worse, on average, in the upper river. Moreover, permeability is higher at 6 inches than it is at the other measurement depths across all sites spanning the upper and middle river (Figure 49). For salmonids, this means that entombment and suffocation associated with infiltration of fine material into clean, newly built redds is unlikely to be significant over the course of a single, several-month-long, spawning-to-emergence period. This would be inconsistent with hypothesis 3, because it suggests that gravel quality may not be declining by much over time.

4.3.3 Synthesis of evidence for hypothesis 3

For hypothesis 3 to be reasonable, there should be evidence indicating that bed-surface mobility has decreased significantly throughout the upper river, and that fine sediment concentrations in the subsurface of the channel bed have increased substantially over time. Our analysis of available data indicates that there has indeed been a significant decrease in mobility of the bed surface over time, due to dam-related coarsening and changes in the magnitude-frequency relationship of flow. On the other hand there is virtually no support for an increase in fine sediment concentrations in the bed. This is due, in large part, to a paucity of quantitative baseline data (i.e., from before 2005) on fine sediment concentrations and permeability. More quantitative conclusions about changes in fine sediment concentrations in the subsurface should be possible in future studies, with the help of the baseline permeability data presented here. Taken together, the balance of evidence does not support hypothesis 3. More conclusive tests will be needed in future studies.

4.4 Revised Conceptual Model of Changes in Spawning Gravel over Time

Not all of our hypotheses about changes in spawning gravel over time were supported by the gravel study data and analyses. Here we integrate our new findings into a revised conceptual model of changes in spawning gravel over time on the Sacramento River below Keswick Dam.

Prior to the arrival of European settlers, the upper and middle sections of the Sacramento River presumably behaved much like other alluvial reaches of unregulated rivers. Local scour during high flows generally would have been offset over the long term by deposition of sediment from upstream sources, local tributaries, and mainstem bank erosion (in the middle river, where lateral migration rates are significant). This would have kept the in-channel supply of spawning gravel roughly constant, despite transient effects of episodic sediment delivery (e.g., from landslides upstream) and extreme flow events.

Construction of Shasta and Keswick dams in the 1940s altered mainstem flow and sediment supply, and thus affected the quantity and grain-size distributions of gravel in the channel downstream. Dam-related reductions in sediment supply were exacerbated by aggregate mining. Remnant in-stream mining pits continue to affect the system by disrupting the continuity of sediment transport, trapping bedload as it is delivered by flow from upstream. Ongoing in-stream mining in tributaries (e.g., Clear Creek, Cottonwood Creek, Reeds Creek, Red Bank Creek, and Thomes Creek) also continues to affect coarse sediment supply to the mainstem (Buer 1994). Tributary sediment contributions along the upper Sacramento River are insufficient to offset the systemic deficit of coarse sediment supply from the above RM 302. Much of the upper Sacramento River (from RM 302 to approximately RM 273.5) is bounded by erosion-resistant bedrock and terrace deposits (CDWR 1980), such that bank erosion is not fast enough, relative to in-channel transport, to provide a significant source of coarse sediment.

Without a supply of spawning-sized gravels to replenish material scoured and routed downstream by post-dam flow releases, the channel bed downstream of Keswick Dam (RM 302) became progressively coarser, as large cobbles were left behind in armor-like lag deposits on the bed (Figure 5; Figure 21). This in turn altered the extent and quality of salmonid spawning habitat. Surfaces have become too coarse for spawning over extensive areas at two historically important spawning sites (Figure 44 and Figure 45). Observations from the Sacramento River suggest that Chinook salmon cannot spawn at sites where more than 40% of the surface is covered by particles with intermediate axis diameters > 130 mm (Figure 46).

Under a typical coarsening scenario in a reach, we expect that spawning gravel would initially become limited to hydraulically protected areas along banks and behind large boulders, where shear stresses are locally suppressed. Relatively fine gravel and spawning could persist in such locations for extended periods, but could be slowly depleted with successive high flows. Our data and observations are broadly consistent with these expectations. Spawning boundaries appear to contract towards channel margins at sites where spawning area losses have been progressive over time (Figure 44). We suggest this is consistent with the observation, based on grain size trends for the upper river as a whole (Table 11), that deposits are becoming increasingly depleted of fine- to medium sized gravel. As of the mid to late 1980s, remaining spawning in the upper river occurred, for the most part, on relict riffles, point bars, and channel-margin deposits where local hydraulics prevent high flows from eroding the remaining gravel and fine cobbles which make the features suitable for spawning (Figure 20).

Gravel augmentation activities in the uppermost river miles (RM 302–298) have locally offset the deficit in coarse sediment supply. However, augmentation volumes have been small relative to the overall deficit in supply and concentrated above the in-stream mining pit at Turtle Bay (Figure 18). There is also little sediment input from tributaries on the upper Sacramento River (Figure 17; Table 8). Bed-surface coarsening has consequently propagated downstream (Figure 54) as successive high flows have progressively depleted in-channel storage (Figure 54) and trapped suitable spawning gravel beneath an armor layer (Figure 21). Although we can point to abundant evidence of coarsening in the upper river, we lack conclusive evidence about how quickly it propagated through the system, due to an absence of data from the first 40 years after the dams were built. Indications from changes in grain-size distributions from after 1980 suggest it has, at most, only weakly affected reaches downstream of Cow Creek (RM 280) (Table 11). However, we cannot rule out the possibility that a wave of coarsening had already propagated as far downstream as Cow Creek (RM 280) and beyond by 1980. If this is the case, then much of the increase in grain size may have gone undocumented, before the first quantitative data was collected in the late 1970s for the 1980 report (CDWR 1980). Sediment transport modeling corroborates this speculation by predicting that significant dam-related coarsening should have propagated downstream to at least as far as RM 290 by 2006, at the end of the simulation (Figure 54 and Figure 56).

Hence, our data and results are inconclusive about whether the effects of the sediment supply deficits are restricted to the reach above Cottonwood Creek. Although the coarse sediment load of Cottonwood Creek probably helps maintain deposits locally, it is too small to offset the overall deficit in supply from the upper river, and probably does not have a long-reaching influence on spawning downstream. If coarsening is occurring downstream of Cottonwood Creek, the implications would be especially severe for the fall run, which have more extensive downstream spawning limits, relative to the other races.

Flows mobilize coarse sediment less frequently if in the post-dam era, due to increases in grain size (Table 11; Figure 44; Figure 45) and changes in the frequency-magnitude relationship of flow. Volumes of injected gravel have been too small to offset the annual sediment supply deficit let alone restore in-stream storage to pre-dam levels. An inevitable consequence of bed mobilization in the absence of supply is continued coarsening in the upper river. This would be consistent with grain size trends (from our statistical analysis; see Table 11) and predictions from sediment transport modeling (Figure 54), which suggest that coarsening of the upper Sacramento River will continue unless the rate of gravel augmentation is increased substantially. This implies that the bed and point bars will become increasingly static, such that fossilized remnants of gravel will be all that remains of once abundant spawning habitat in the river's spawning reaches.

For much of the upper river, only sand and finer sediment has remained mobile on a bed that has become increasingly immobile over time due to progressive coarsening of the surface and the reduced frequency of peak, bed-scouring flows. This should lead to enhanced intrusion of fine sediment into the subsurface of the bed, particularly if dam-related reductions in fine sediment supply have not been too substantial. However, it is difficult to identify whether fine sediment concentrations in the subsurface are increasing, due to a paucity of data on historical conditions. Hence we cannot confidently say whether rates of fine sediment accumulation are fast enough to have degraded the quality of spawning gravel in the upper river.

In the middle river, grain-size data and spawning area assessments are consistent with no systematic changes over. Scour observations and the historical planform data confirm that the middle river's bed and banks are highly mobile from year to year. The annual exchange of sediment from deposit to deposit appears to be substantial. In particular, scour can be significant enough (>1 m) to excavate redds, killing eggs and alevin if it occurs during incubation (Table 15). This could affect the fall run because they can emerge in early winter, when flows are periodically high enough to mobilize the bed. Other races are not generally affected by scour because they do not use the scour-prone middle river for spawning. Exceptions probably occur in the upper river, at gravel augmentation sites, where scour may be significant due to the homogeneity and loose packing of injected gravel relative to natural bed deposits.

The relatively high throughput of gravel and fine sediment in the middle river ensures that few, if any, of the riffles are too coarse for spawning (Figure 21; Figure 27). However, middle river deposits are no worse than upper river deposits; permeability shows no clear trend with river mile (Figure 49). Many of our sites would be unsuitable for spawning unless the redd-building process cleans them sufficiently to increase their permeabilities, and thus raise their estimated survival indices above the universally poor values indicated in Figure 49. Although we have no reason to suspect that permeability has changed systematically over time in the middle river,,we cannot confirm this because there are no previous data on permeability for the river.

The middle river exhibits (i) broad-scale stability of spawning area (Buer 1984), (ii) a relatively high likelihood of scour and mobility (Table 15), and (iii) historical evidence of sweeping changes in channel planform at the local scale (CDWR 1980). The channel and banks of the middle river may be in a state of approximate dynamic equilibrium with respect to sediment flux. Under such a condition, losses in gravel (and spawning area) in any given reach are offset by gains in other reaches, such that the overall area remains roughly constant despite sometimes dramatic year-to-year shifts in channel position. This is consistent with independent sediment transport modeling results (Singer and Dunne 2004), which suggest that erosion and deposition throughout the middle river are in a rough balance.

5 PRINCIPAL FINDINGS AND IMPLICATIONS

The gravel study was designed to quantify how the quality, quantity, and dynamics of spawning gravel have been affected by changes in flow and sediment supply in the mainstem below Keswick Dam (RM 302). Principal findings and implications of the study include:

1. Analysis of the spawning area surveys shows:
   - From 1964 to 1980, there appears to have been a significant loss in spawning area in two subreaches of the upper river (from RM 298 to RM 292 and from RM 289 to RM 283). Spawning area appears to have been much more stable in the immediate downstream vicinity of sediment-bearing tributaries (Figure 17). These observations are consistent with coarsening, locally ameliorated by small amounts of sediment supply from the tributaries. Our interpretation of the 1964 and 1980 data is broadly consistent with conclusions of CDWR (1980, 1995)—i.e., that the changes in spawning area between the 1964 and 1980 surveys are suggestive of a loss of gravel that can be attributed at least in part to the effects of bed coarsening in the reach (from RM 302–283). However, it is contingent on the assumption that the fall run was abundant enough in 1980 that they "saturated" the available spawning area with redds.
   - By 2005, extensive new spawning areas had developed upstream of ACID dam (Figure 17), presumably in response to gravel injections at Keswick Dam and Salt Creek (Figure 18) that have apparently helped locally offset losses due to the systemic, dam-related deficit in coarse sediment supply. Like the 1980 survey data, the 2005 data show a significant loss in spawning area from RM 298 to RM 292, relative to results from 1964 (Figure 17). Taken together, these observations are consistent with coarsening, with amelioration by the offsetting effects of gravel augmentation. We can be fairly certain that our assumption about the saturation of redds was reasonable in 2005 and (to a lesser extent) in 1964, based on population trends and observations that are consistent with saturation during our 2006 facies mapping field work (see Figure 19, Table 10, and accompanying text).

2. Reach-scale analysis of grain size and spawning area from the facies mapping work reveals:
   - Spawning area losses have occurred in at least two key upper reaches, Redding Riffle (Figure 45) and RM 292 (Figure 44), despite repeated gravel augmentation activities at the Redding Riffle site (Figure 18). Some of the losses may be due to coarsening, which is presumably associated with the systemic, dam-related deficit in coarse sediment supply.
   - Spawning area losses in reaches downstream of RM 292 are not clearly evident, although significant shifts in the locus of most intensive spawning is often present (Figure 41; Figure 42; Figure 43). This is broadly consistent with results from sediment transport modeling, which predict a localized, partial recovery of in-stream sediment storage (Figure 53) and median grain size (Figure 54) between RM 295 and RM 290 in response to recent gravel injections in the reach. The effects of small contributions of sediment from Clear Creek may also be important at the downstream-most site (Figure 41). The shifts in spawning distribution that have occurred below RM 292 may be related to local conditions (i.e., the presence/absence of tributaries and gravel augmentation) rather than the systemic, dam-related change in sediment supply.

- Added gravel has enhanced existing spawning habitat in the key winter-run spawning reach (RM 302–289), (Figure 41; Figure 43; Figure 45).

Taken together, the facies mapping results suggest that coarsening has been significant in two reaches between RM 298 and RM 292 (Figure 44; Figure 45).

3. Chinook salmon of the Sacramento River are not able to spawn in deposits where ≥40% of the surface is covered by particles with intermediate-axis diameters >130 mm (Figure 46). Assessing the percent coverage by immovable particles, together with hydraulic conditions, can provide a quick, powerful, diagnostic tool for assessing the suitability of spawning gravel in rivers where spawning may be limited by the abundance of very coarse material on the surface.

4. Point-bar-scale variations in grain-size distributions preclude meaningful comparisons of year-to-year changes at individual sites. Any assessment of changes in grain size over time requires characterizing the river in broad strokes (e.g., as in Figure 40), over the scale of entire deposits or long reaches.

5. The methods used to collect bulk samples in 1980 in the upper river (CDWR 1980) were biased towards fine-grained sites and yielded sample sizes that were too small to be statistically representative. In contrast, methods used to collect bulk samples in 1995 (CDWR 1995) and 2005 (this study) were more statistically robust and unbiased with respect to grain size. Bulk sampling results from 1980 (Figure 25) are thus incompatible with bulk sampling results from 1995 (Figure 22) and 2005 (Figure 21).

6. Standard statistical regression analysis shows that surfaces have become depleted of spawning-sized gravel since at least as far back as 1980 in deposits upstream of Cow Creek (RM 280) (Table 11). Most of the losses in habitat are focused in what would generally be classified as highly suitable deposits—where median grain size is order 50 mm (Figure 37; Figure 40). In the absence of grain size data from before 1980, we are unable quantify any changes that may have occurred in the first four decades after dam construction. We suspect they were significant, based on sediment transport modeling (Figure 54; Figure 56) and the indication, from the spawning area observations (Figure 17), that the largest losses of overall spawning area for the upper river as a whole may have already occurred by 1980.

7. Field observations (Figure 44; Figure 20) suggest that spawning in the upper river has become increasingly restricted to relict deposits along channel margins and on fossilized point bars. Indications that spawning-sized gravels are becoming increasingly scarce (principal finding 6; Figure 37; Figure 40; Table 11) suggest that the spawning suitability of these relict deposits is declining.

8. At some sites in the middle river, scour can be significant enough (>1 m; Table 15) to excavate redds, killing eggs and alevin if it occurs during incubation. This could affect the fall run (the only race to use the scour-prone middle river for spawning) because they emerge in early winter when flows are periodically high enough to mobilize the bed. Effects of scour on other Chinook salmon races are probably limited to gravel augmentation sites, where injected spawning gravel may be prone to excessive transport if it is not integrated into the coarse, armored surface of natural deposits.

9. Permeability is not correlated with river mile for any of the measured gravel depths. It is higher overall in the upper 6 inches of the bed than it is at depth across the series of sites

considered in this study (Figure 49). This indicates that the upper part of the bed is relatively free of fine material, and that fine sediment infiltration is probably not fast enough to cause substantial entombment or suffocation of eggs and alevin in any given survival-to-emergence cycle.

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FIGURES

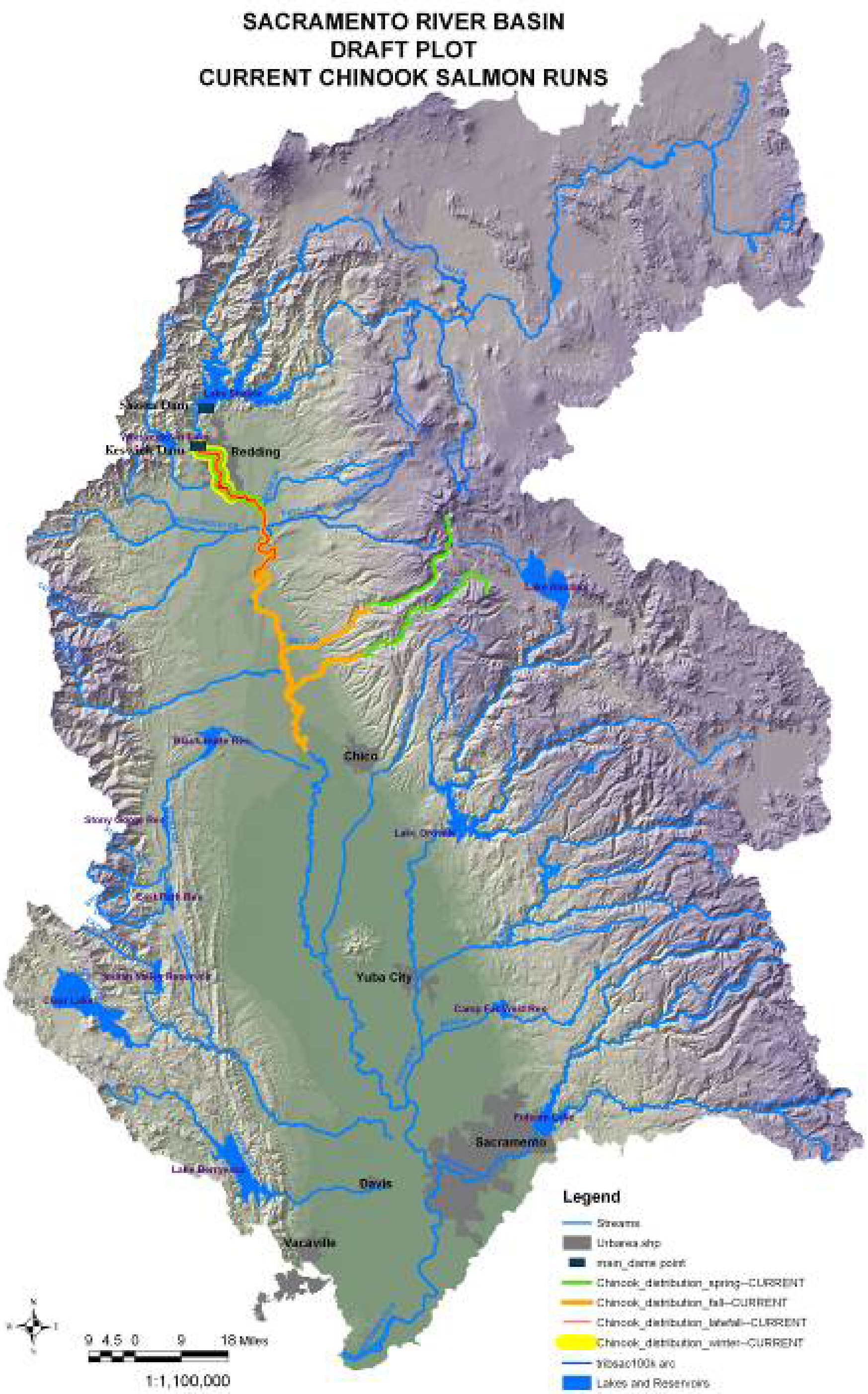


Figure 1. Sacramento River watershed map showing estimated current extent of spawning for each of the basin's four Chinook salmon races.

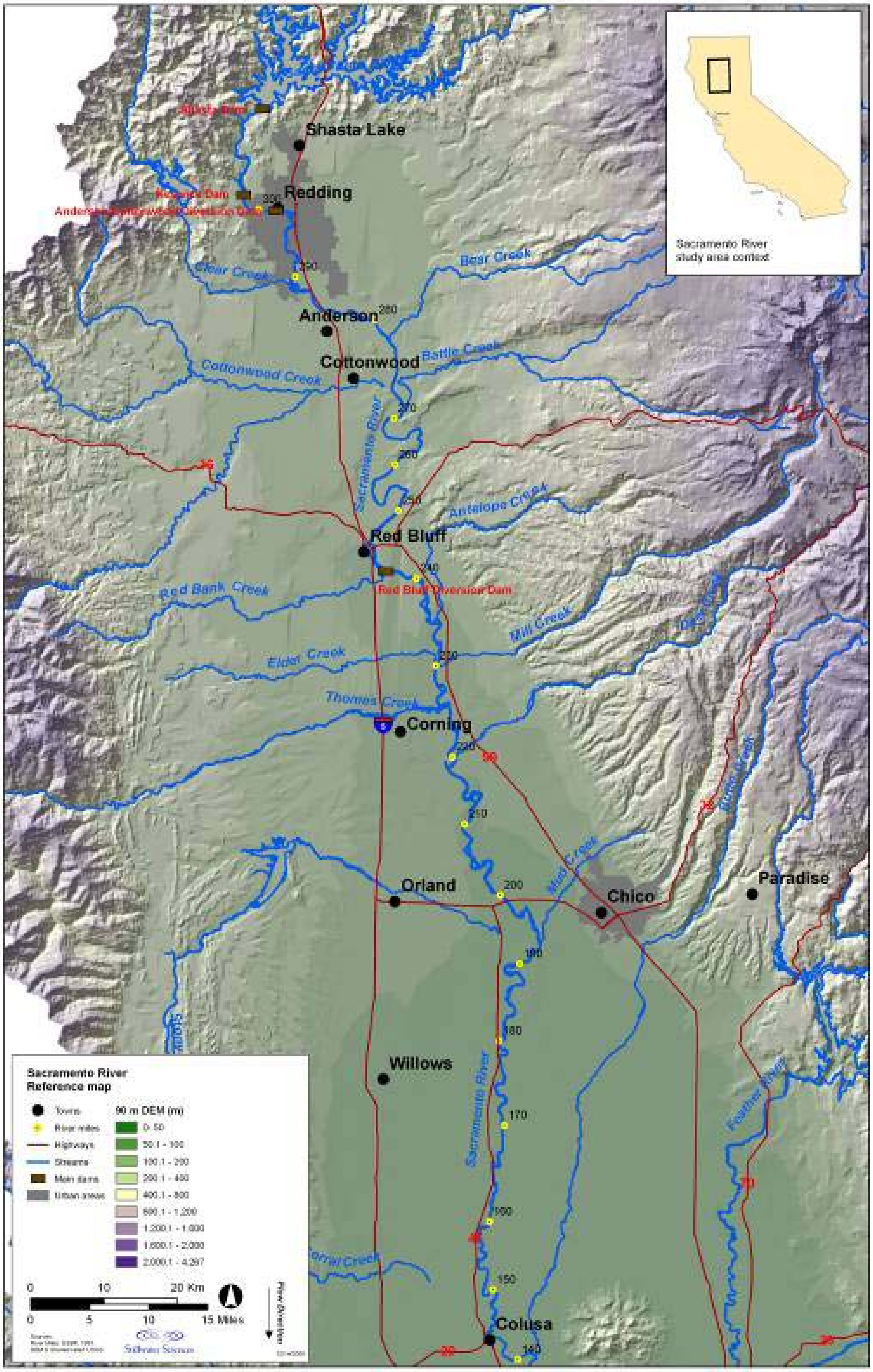


Figure 2. Shaded relief map of the northern Central Valley of California. The study area of the Sacramento River Ecological Flows Project extends along the mainstem from RM 302 (at Keswick Dam) to RM 143 (at Colusa).

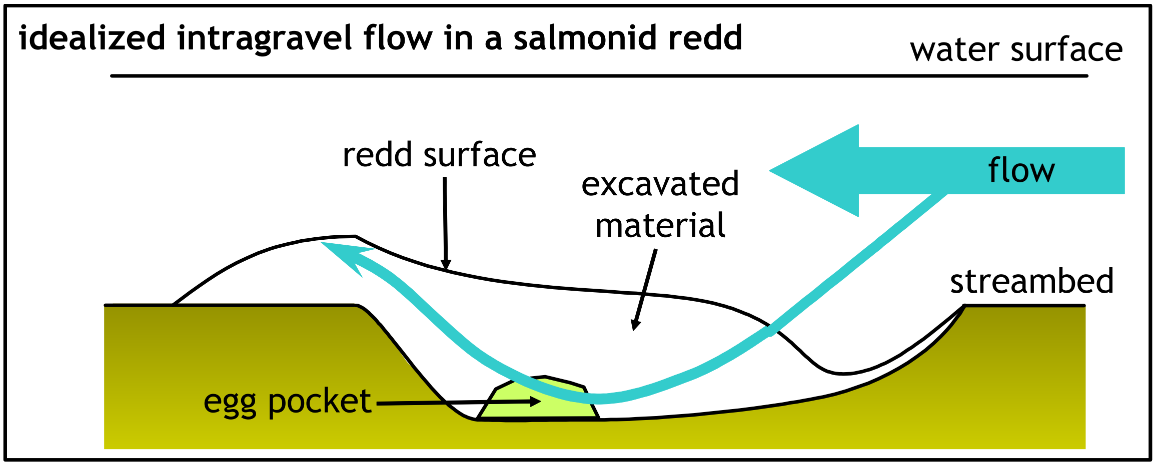


Figure 3. Conceptual diagram of intragravel flow through a buried salmonid egg pocket. The redd imposes a perturbation to the streambed profile, creating hydraulic conditions that force flow through the egg pocket.

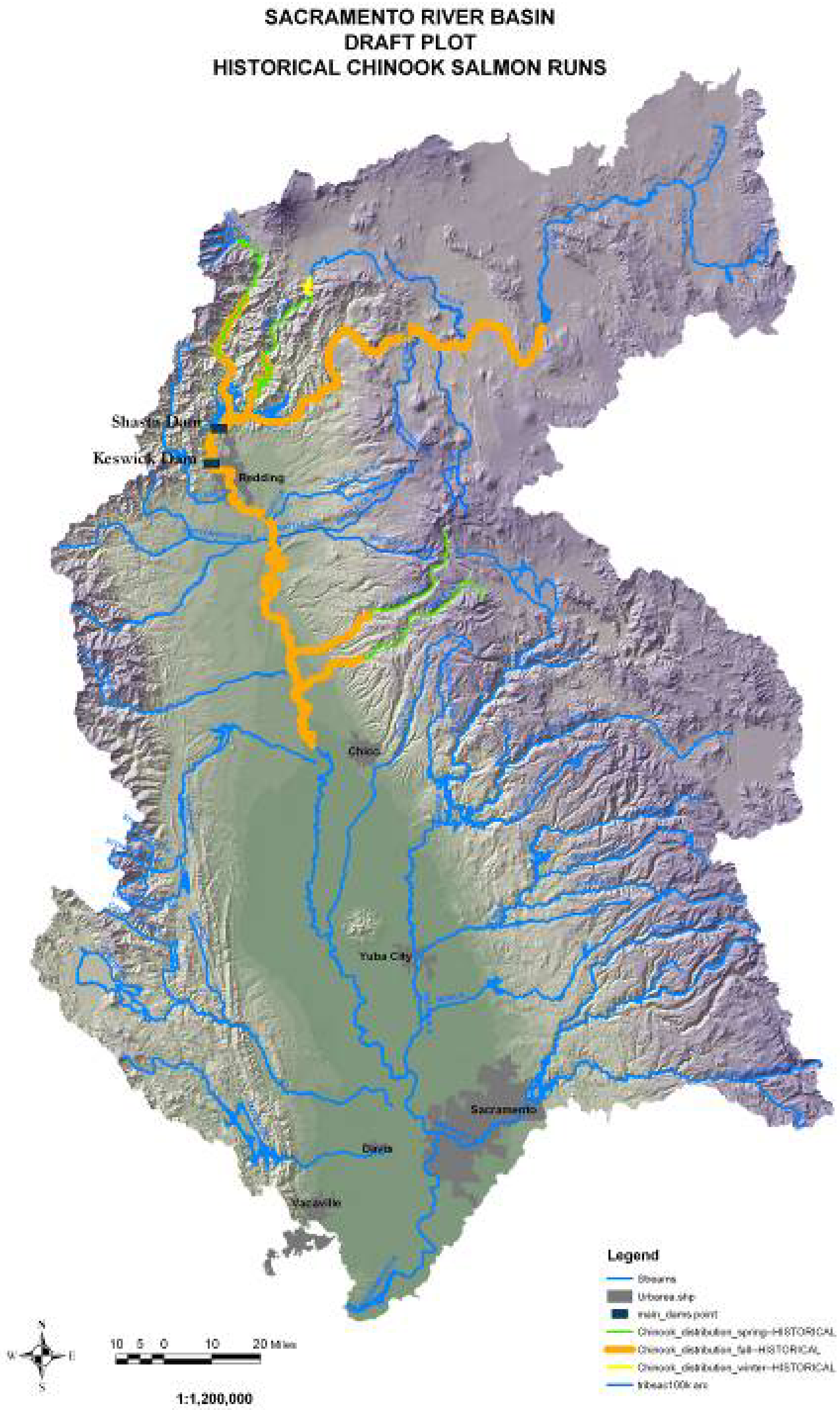


Figure 4. Sacramento River watershed map showing estimated historical extent of spawning for three of the basin's Chinook salmon races. Comparison of this map with the one shown in Figure 1 illustrates how the extent of spawning has been greatly reduced relative to historic conditions.

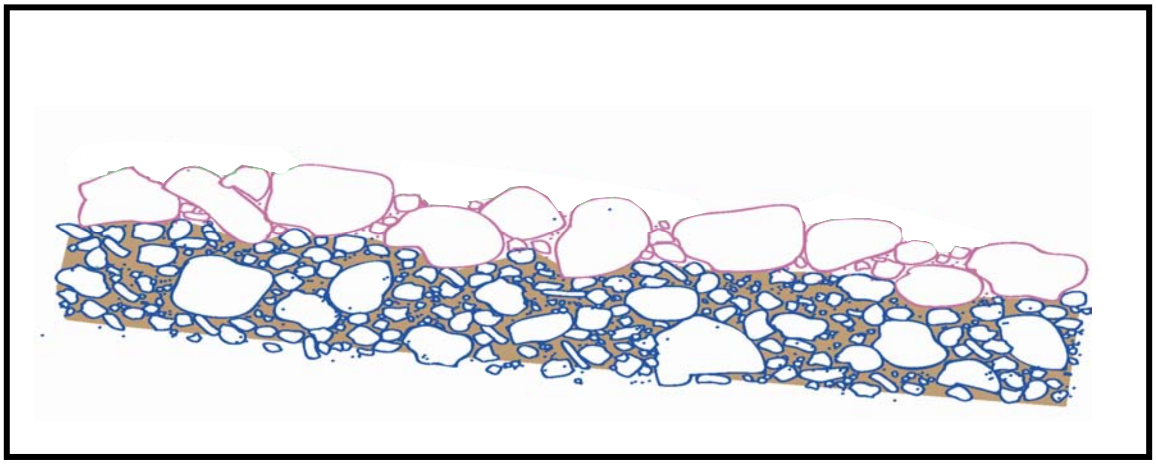


Figure 5. Schematic profile of sediment near the surface of a streambed. A coarse surface layer (pink) overlies a finer subsurface layer (blue). Surface coarsening is an inevitable result of selective transport in the absence of sediment supply. On the Sacramento River, the surface has locally become so coarse that salmonids are no longer able to break through it to spawn in the gravel below. We hypothesize that this may have occurred in many deposits of the upper Sacramento River (Hypothesis 1). We further hypothesize that increased coarsening has been propagating downstream from the dams progressively over time (Hypothesis 2). We also hypothesize that the coarsening process has reduced mobility of the surface such that fine sediment has become trapped beneath it in steadily increasing concentrations, resulting in steadily decreasing spawning gravel quality for a many of the remaining deposits in the post-dam era (Hypothesis 3).

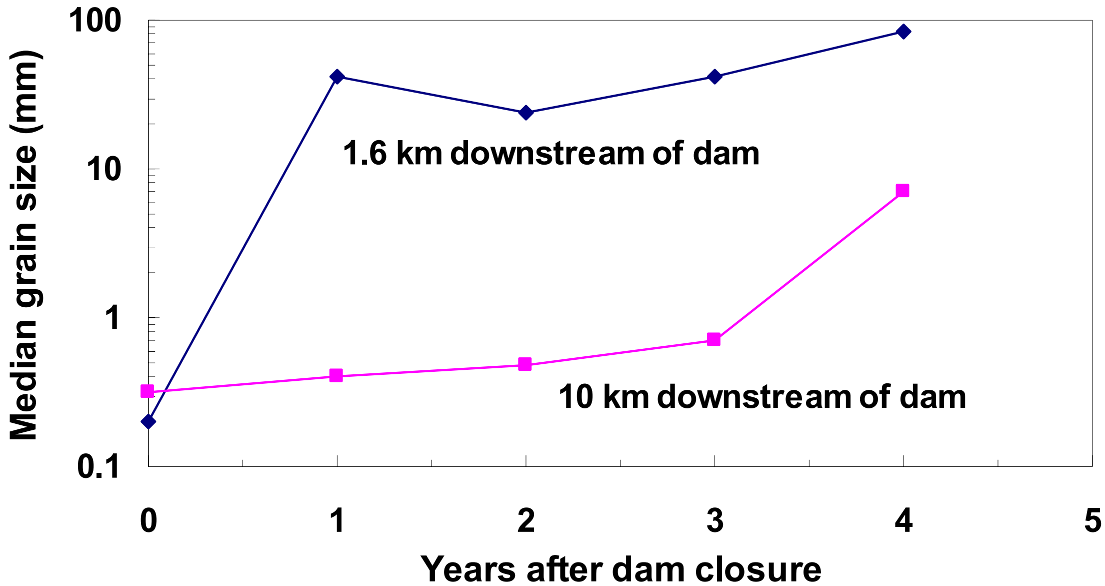


Figure 6. Median grain size as a function of time for two sites on the Colorado River below Hoover Dam. Close to the dam, grain size increased quickly after dam closure. In contrast, grain size at the site farther downstream stayed relatively fine for two years before showing signs of increasing substantially. The delayed response of the more distal site reflects a downstream propagation of surface coarsening after sediment supply was reduced by dam construction. In the case of the Sacramento River, we expect that the coarsening has been less pronounced, because initial conditions below Keswick Dam were much coarser than they were below Hoover Dam. Source: Williams and Wolman (1984).

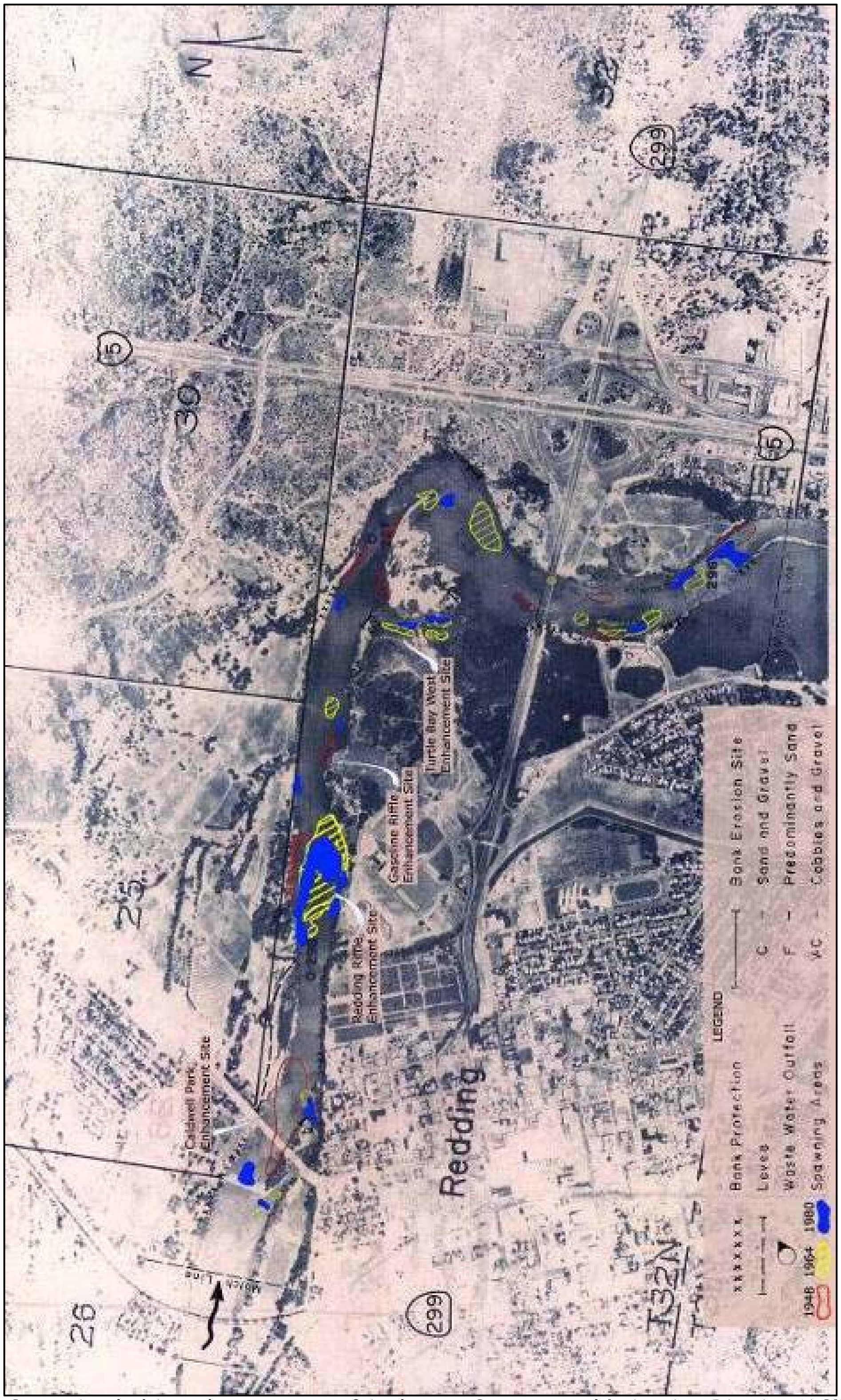


Figure 7. Spawning habitat downstream of Anderson-Cottonwood Irrigation District (ACID) Dam in 1948 (red), 1964 (yellow), and 1980 (blue). Visual inspection of maps like this (spanning the entire upper river) led CDWR (1980) to conclude that spawning area had been lost from 1964 to 1980. They went on to speculate that this supported the hypothesis that there had been a loss of spawning gravel as well. Source: CDWR 1980.

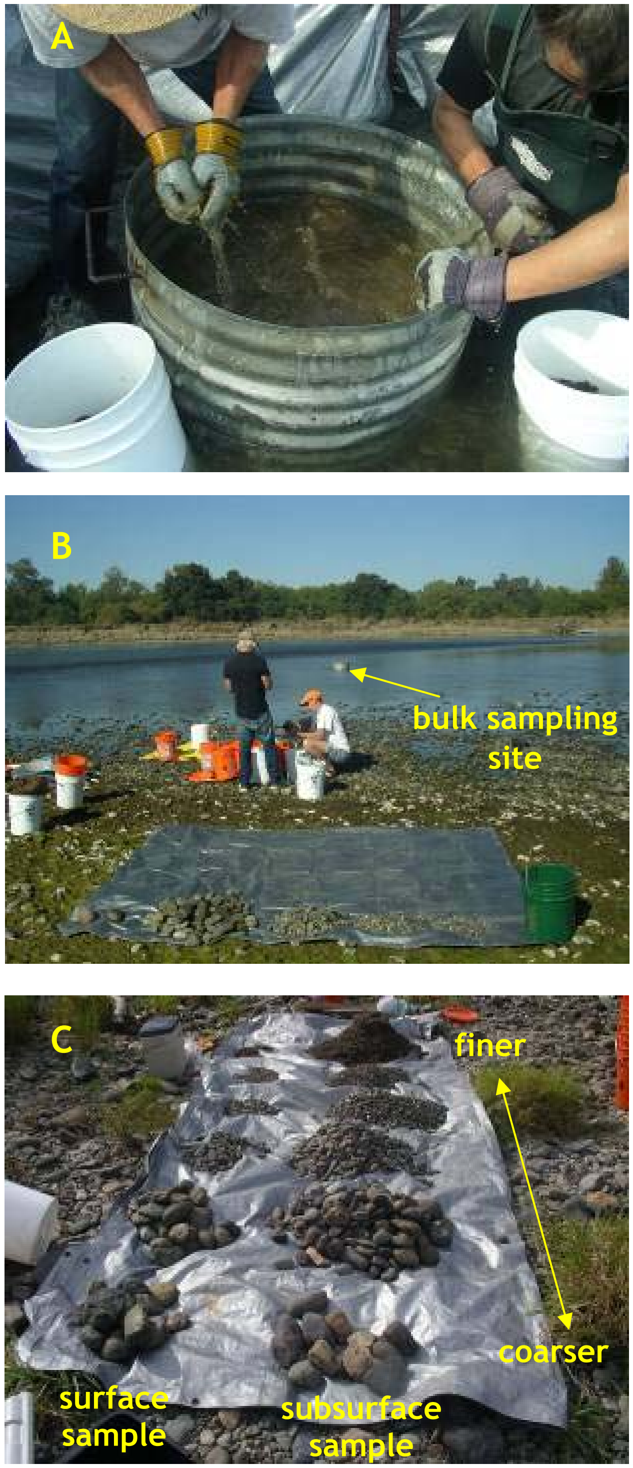


Figure 8. Bulk sampling of surface and subsurface bed samples from the Sacramento River. (A) A section of culvert (30 inch diameter) is worked into the bed and particles from the surface are extracted by hand. (B) Samples are sieved and the mass of each size class is recorded on a nearby bank. (C) Surface (left) and subsurface (right) samples, segregated into size classes for one of the samples from the middle Sacramento River.

Figure 9. Measuring permeability in spawning riffles of the Sacramento River. (A) Permeability standpipe and sipping rod. (B) Permeability backpack.

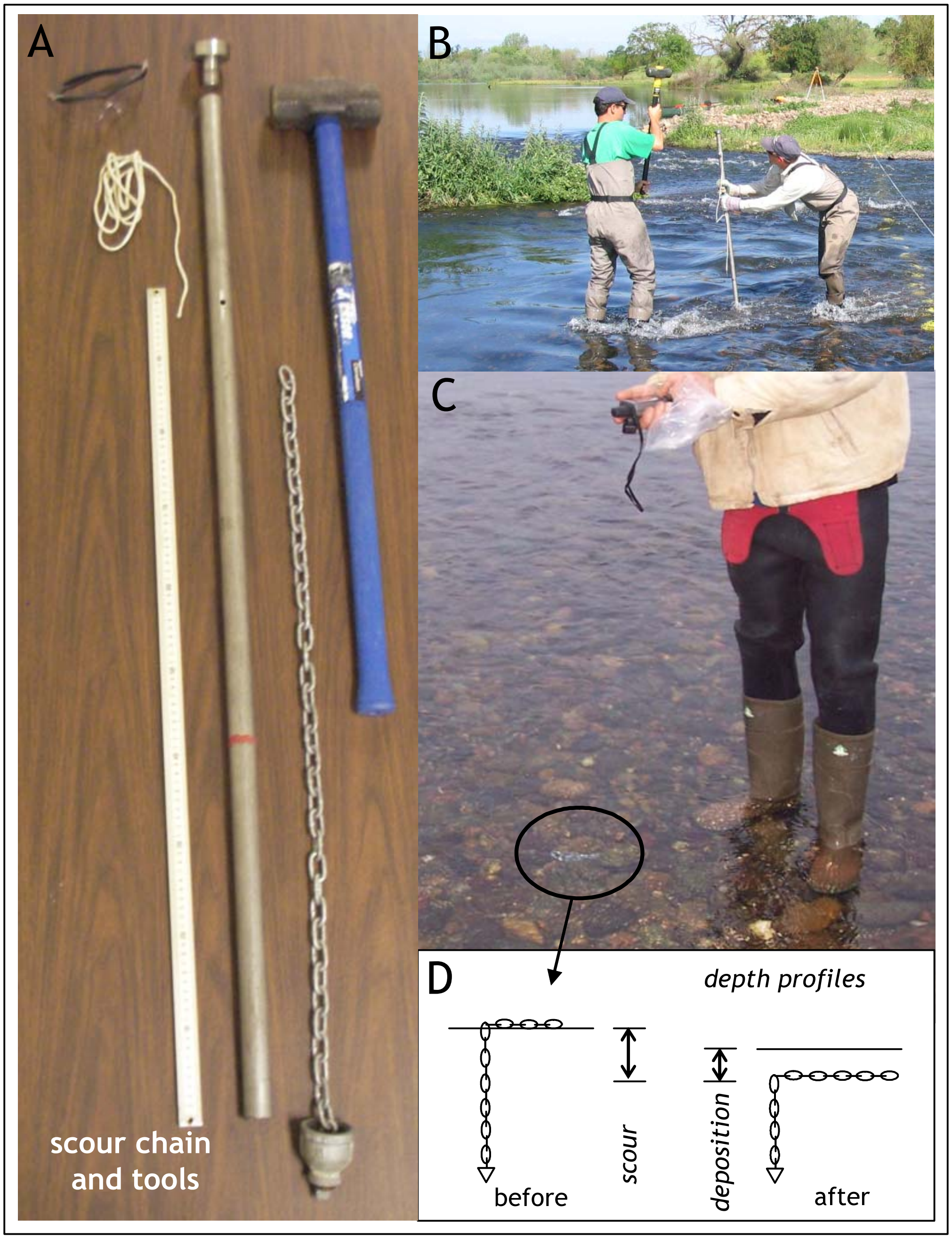


Figure 10. Scour chain installation and monitoring. (A) Scour chain with installation tools. (B) Installation. (C) Scour chains in place in bed after installation. (D) Depth profiles of installed chain before and after a bed mobilizing flow showing monitoring principles: scour can be measured as the difference between the trailing lengths of the chain before and after the flow; deposition (shown in this example to be less than the scour) is measured as the depth to the horizontally oriented length of chain after the flow.

Figure 11. Scour boxes of the Sacramento River gravel study. Scour boxes dimensions were 5' x 5'. Three were installed at each of five sites in the study area. Scour box spacing was 20 m.

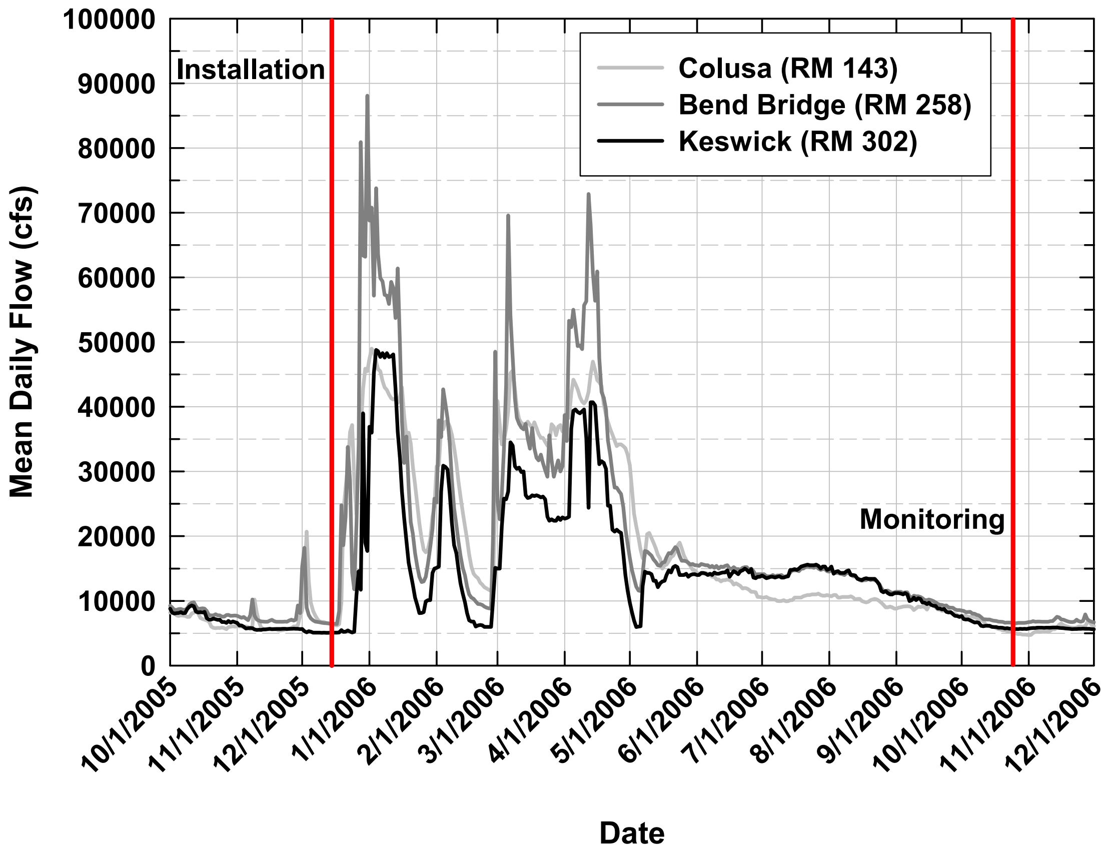


Figure 12. Mean daily flow at Keswick (RM 302), Bend Bridge (RM 258), and Colusa (RM 143), 3 USGS gauges that span the upper and middle sections of the river. Vertical lines mark the installation and monitoring dates of the bed scour study. Daily flow averaged greater than 60,000 cfs at Bend Bridge for 14 days in the interval. The peak daily flow at Bend Bridge was 88,100 cfs. Note that instantaneous peak flows for each of the WY 2006 flood pulses on the Sacramento River would likely plot significantly higher than the mean daily peaks plotted here.

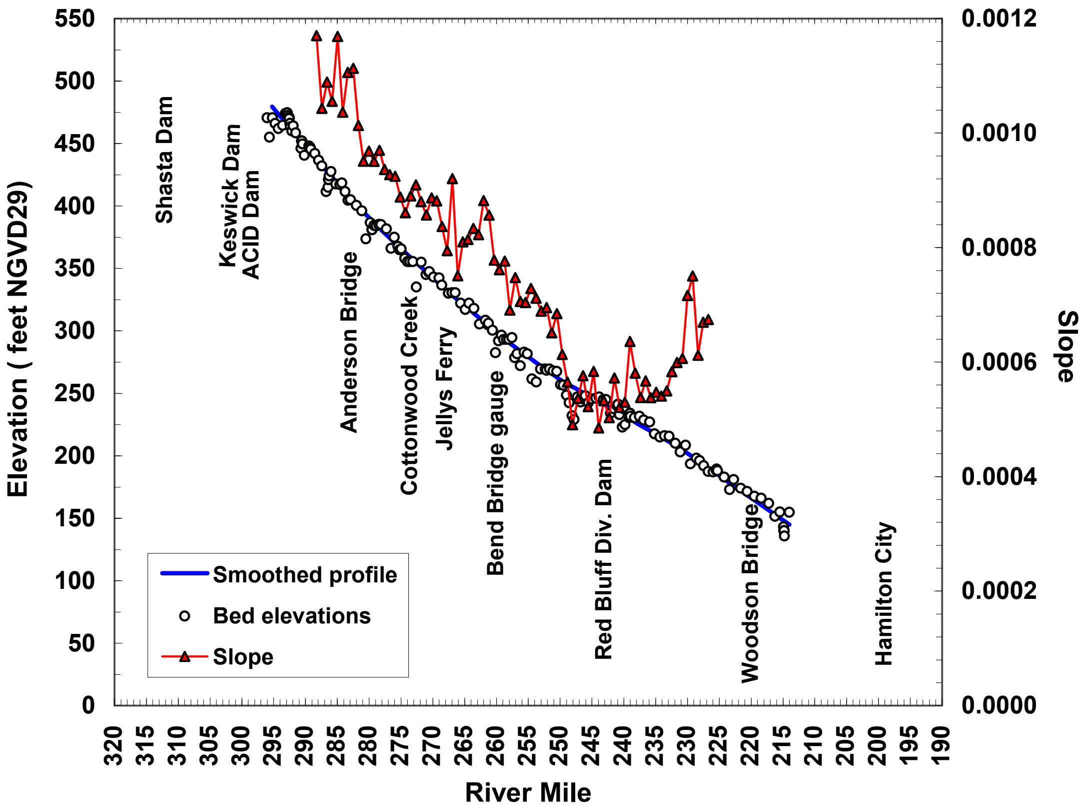


Figure 13. Long profile from 2001 CDWR HEC-RAS modeling of Sacramento River (black circles), with smoothed profile (blue line), and average slope (triangles, in m/m) of the smoothed profile (red line).

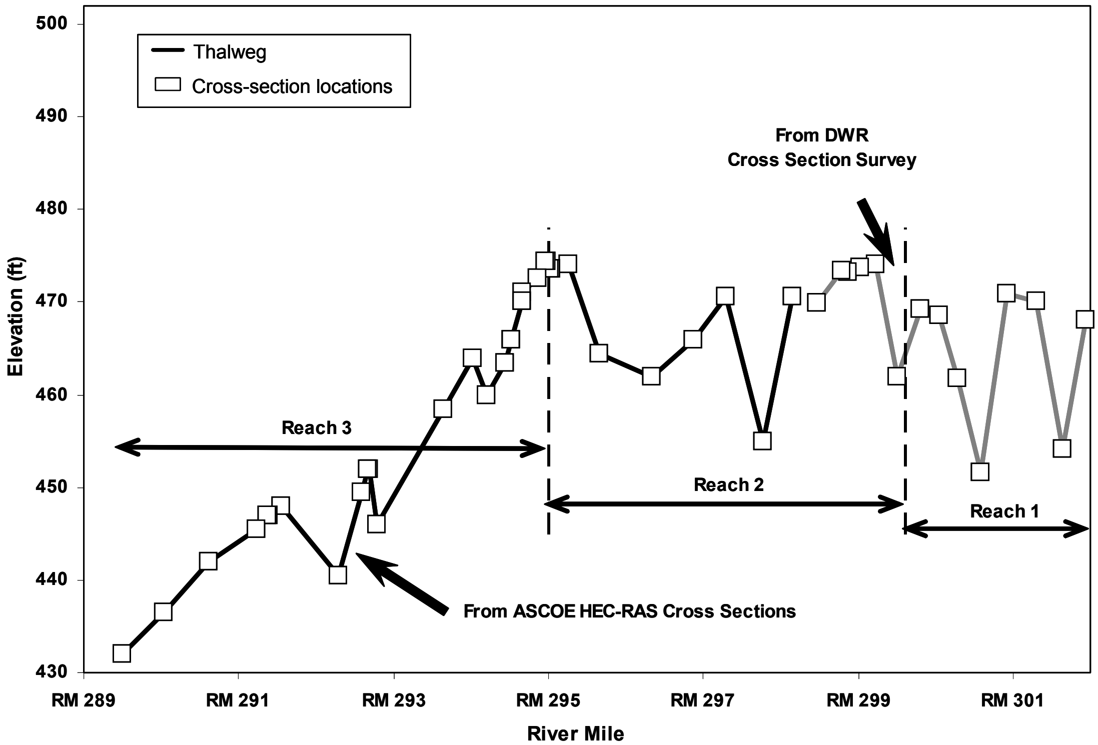


Figure 14. Thalweg profiles for three subreaches where dam-related coarsening is expected to have been most significant. TUGS model was applied to each subreach, but only reach 3 had enough cross-section data to resolve effects of sediment transport on individual spawning areas.

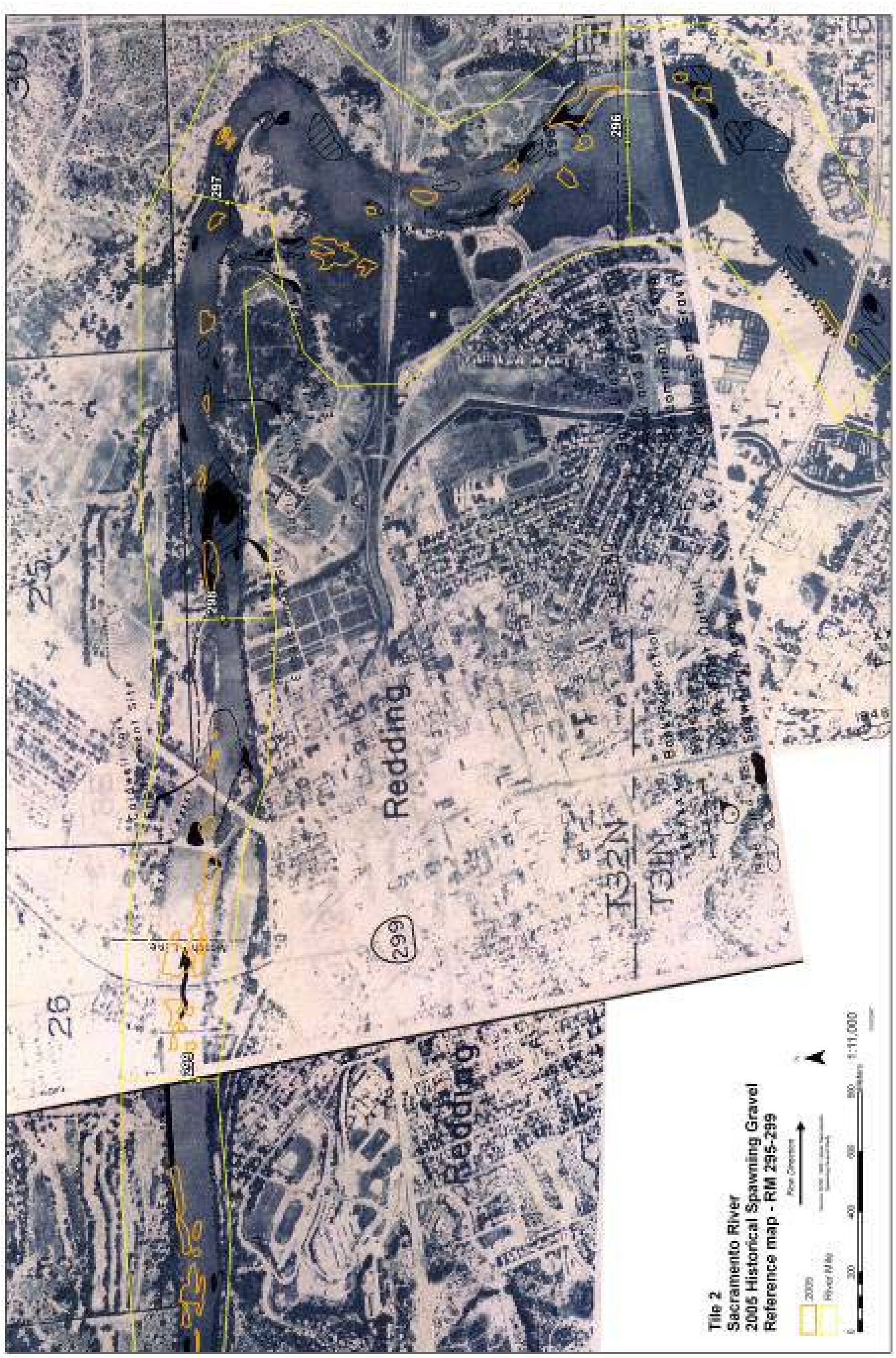


Figure 15. Map showing spawning area polygons from RM 295 to 299. New polygons, mapped from the 2005 survey, are highlighted in orange. From 1980 to 2005 there appears to have been a net increase in spawning area, particularly in the upper end of the reach, where most of the river's gravel augmentation projects have been focused. This suggests that the increase in spawning area as of 2005 reflects the effects of repeated gravel injections. Base map source: CDWR 1980.

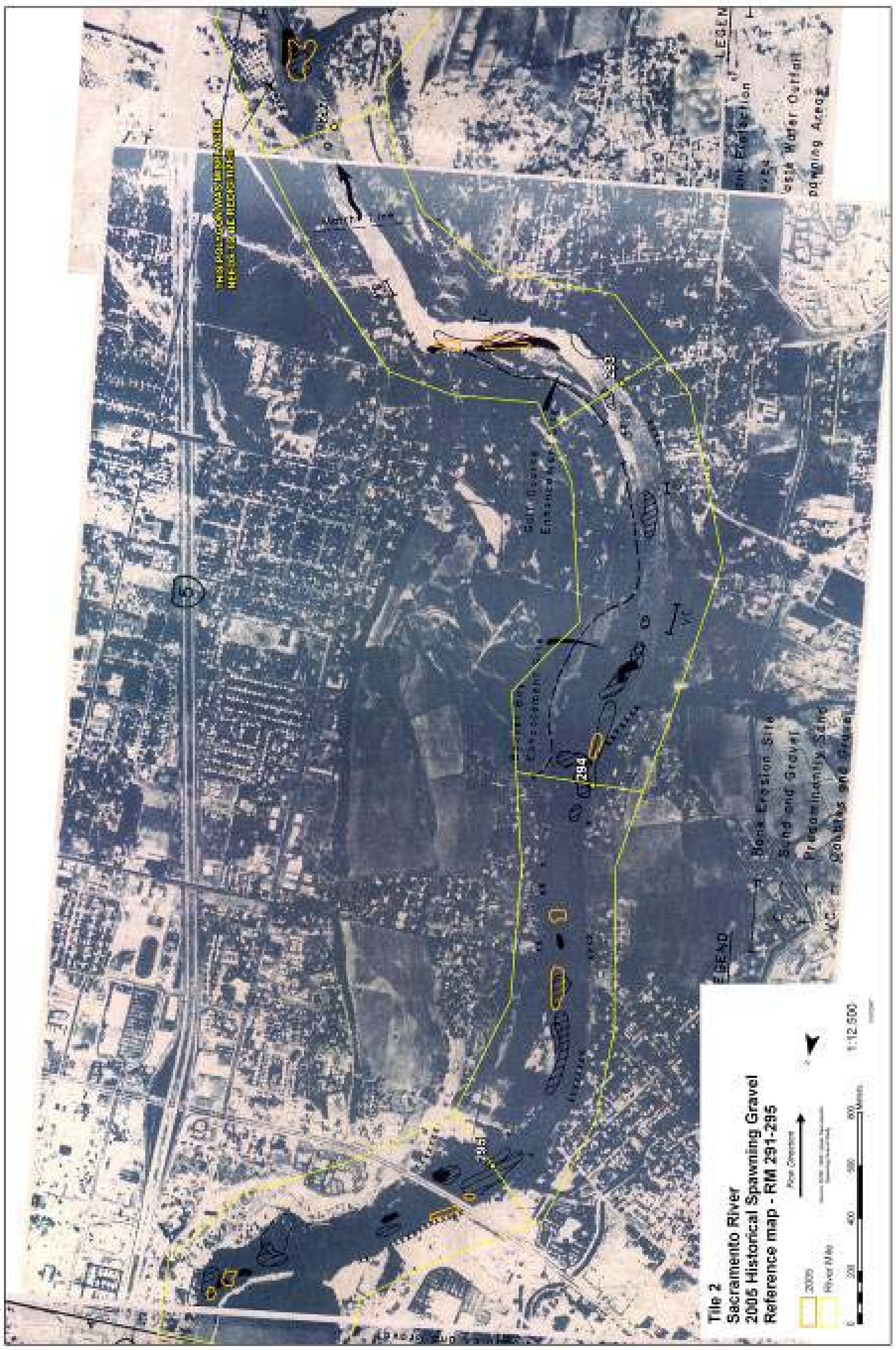


Figure 16. Map showing spawning area polygons from RM 295 to 291. New polygons from 2005 are highlighted in orange. Spawning area appears to have declined substantially since 1964, apparently due to spawning gravel losses associated with dam-related coarsening on the upper river. Base map source: CDWR 1980.

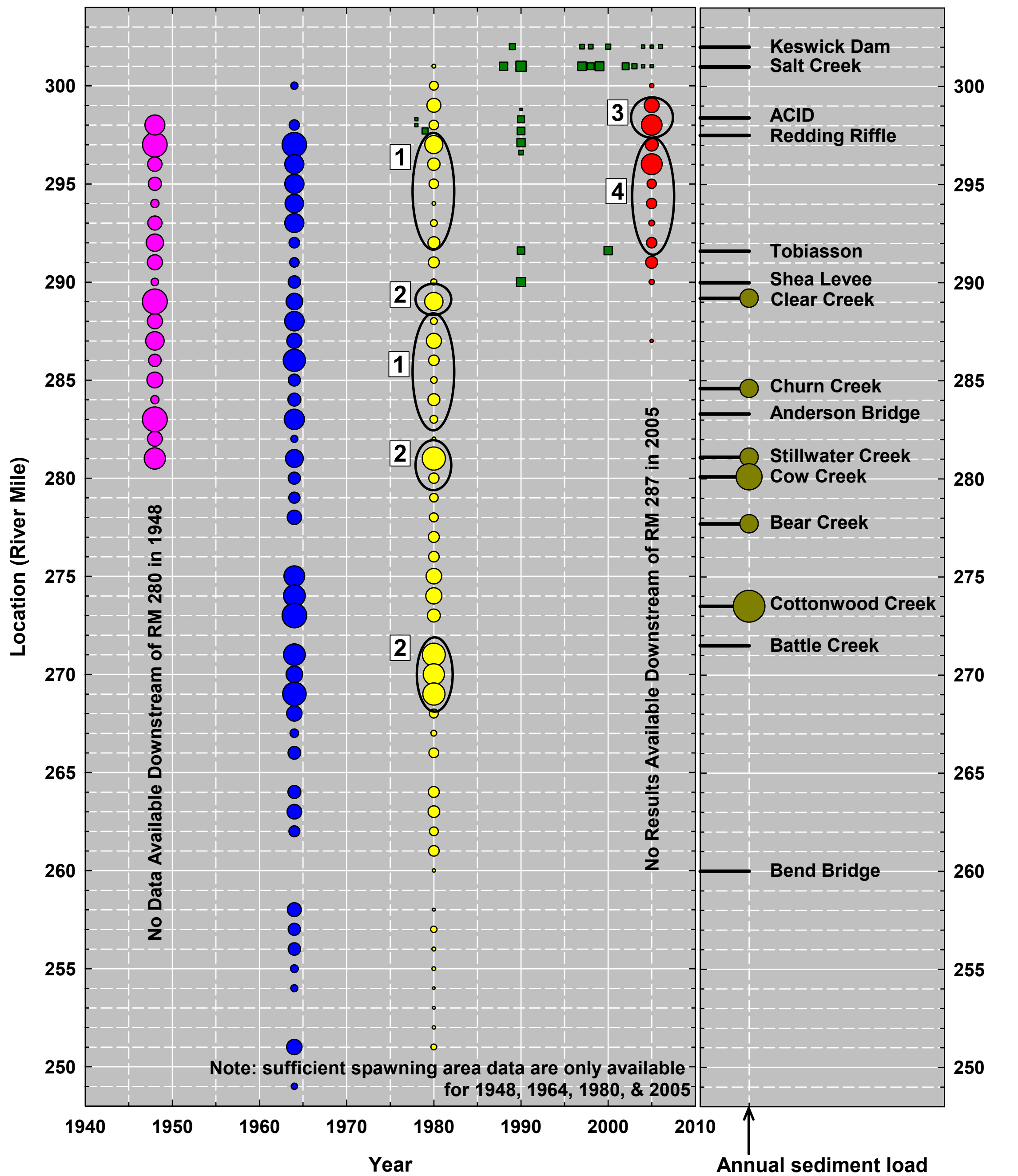


Figure 17. Bubble plot showing spawning habitat area by river mile and year. Surveys of salmonid spawning habitat were conducted in 1948 (pink), 1964 (blue), 1980 (yellow), and 2005 (red). *Note:* Data from 2005 are incomplete; extensive spawning was observed (but not mapped) downstream of RM 290. Spawning area scales uniformly with bubble area. Green squares show location, timing, magnitude of gravel augmentation (see also Figure 18), with injected volume scaled to plot symbol area. The scale on the right shows major landmarks, with relative annual sediment loads (in mass per unit time; Table 8) of tributaries scaled according to brown bubble area. Labeled circles identify four trends discussed in text: (1) A marked decline in spawning area from 1964 to 1980 from Redding Riffle (RM 298) to RM 292 and from RM 289 to Anderson Bridge (RM 283); (2) Roughly stable spawning area in the immediate downstream vicinity of the river's sediment-bearing tributaries; (3) Greatly increased spawning area in the upper-most reaches of the river by 2005, due to local effects of gravel augmentation; (4) persistence of reduced area from Redding Riffle (RM 298) to RM 292 by 2005.

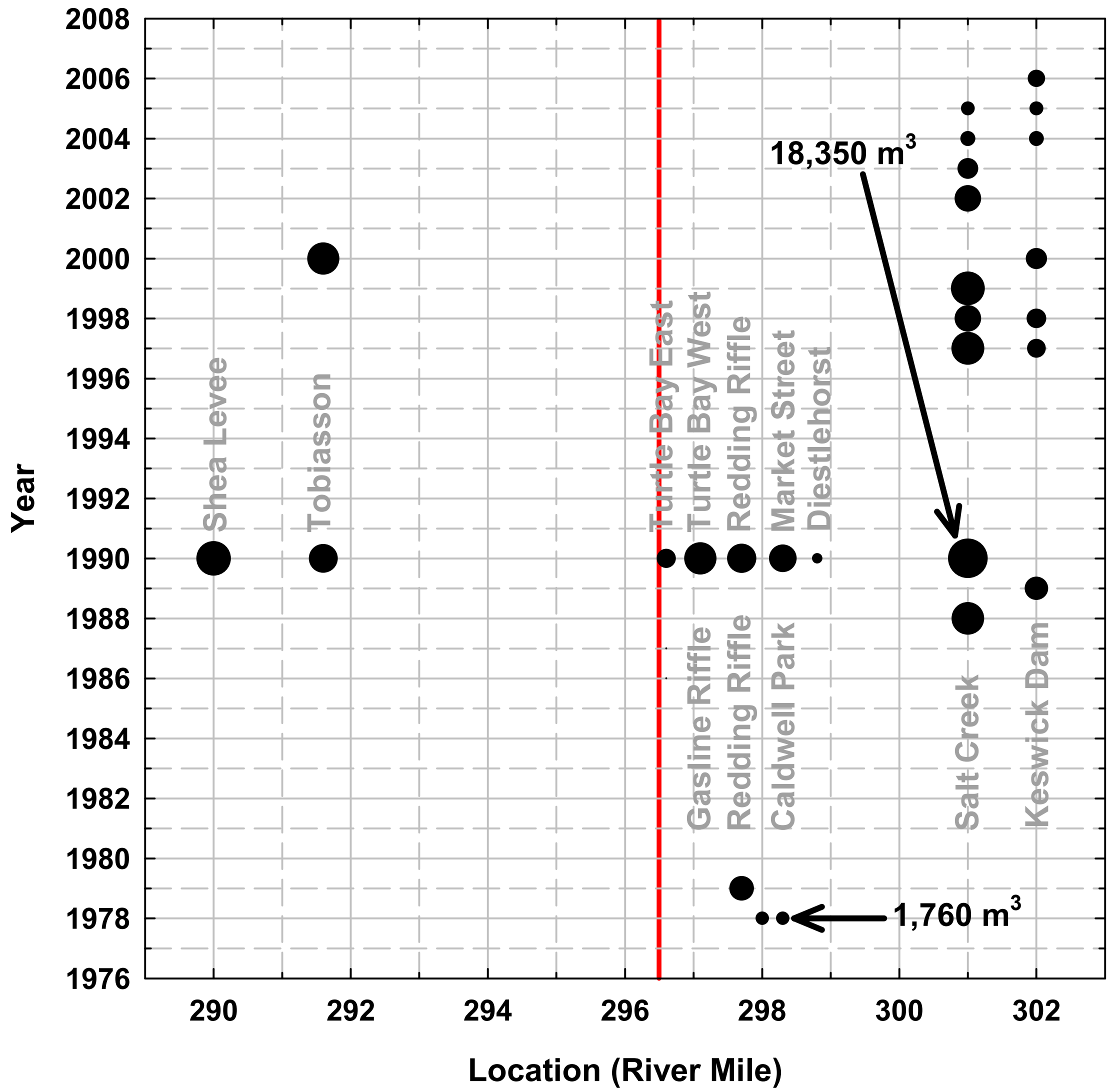


Figure 18. Bubble plot of gravel augmentation by year and river mile for the upper Sacramento River. Bubble area scales proportionally with volume added. The lowest (1760 m^3) and highest (18,350 m^3) augmentation volumes are labeled for scale. Vertical line marks location of Turtle Bay, a deep, remnant in-stream mining pit that can presumably trap much of any sediment in transit from upstream and thus significantly disrupt the continuity of sediment transport of more than half of the gravel that has been added to the river.

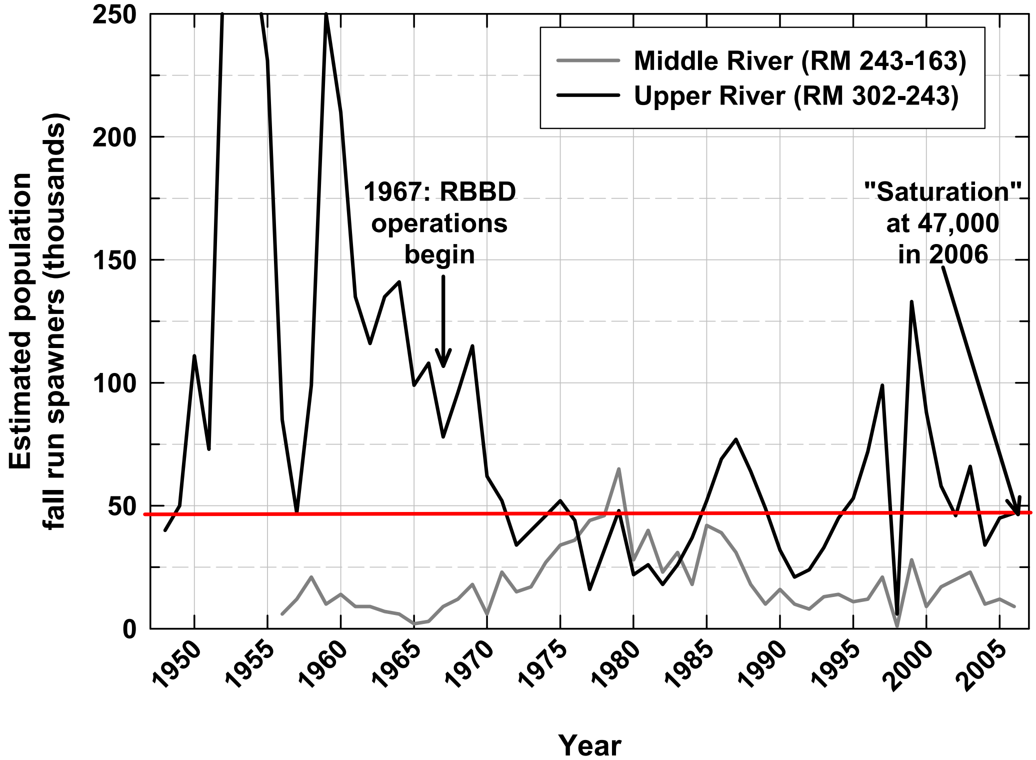


Figure 19. Estimated fall run spawning returns, Sacramento River mainstem. Source: CDFG (2007), except 1948–1956 data (from CDWR 1985; see Table 10). Field observations suggest that fall run returns in 2006 were sufficient to "saturate" available spawning area in the upper river (see text). This implies that the current threshold for saturation by fall run spawners is at least as low as 47,000 fish (red horizontal line). This implies that spawning area was probably saturated with fall run spawners in 2005 (during the helicopter survey) and further suggests that saturation may have occurred in 1964, when the estimated population in the upper river was 141,000 fish. Importantly, the 47,000 fish threshold does not rule out the chance that saturation occurred in 1980, even though only 22,000 fall run spawners returned to the upper river in that year; 47,000 is a minimum bound on the threshold (it could be lower). The late 1960's decline in upper river returns was accompanied by an increase in returns on the middle river, coincident with operation of RBBD, which would have impeded fall run access to the upper river, and thus forced a greater percentage of the run to spawn in the middle river.

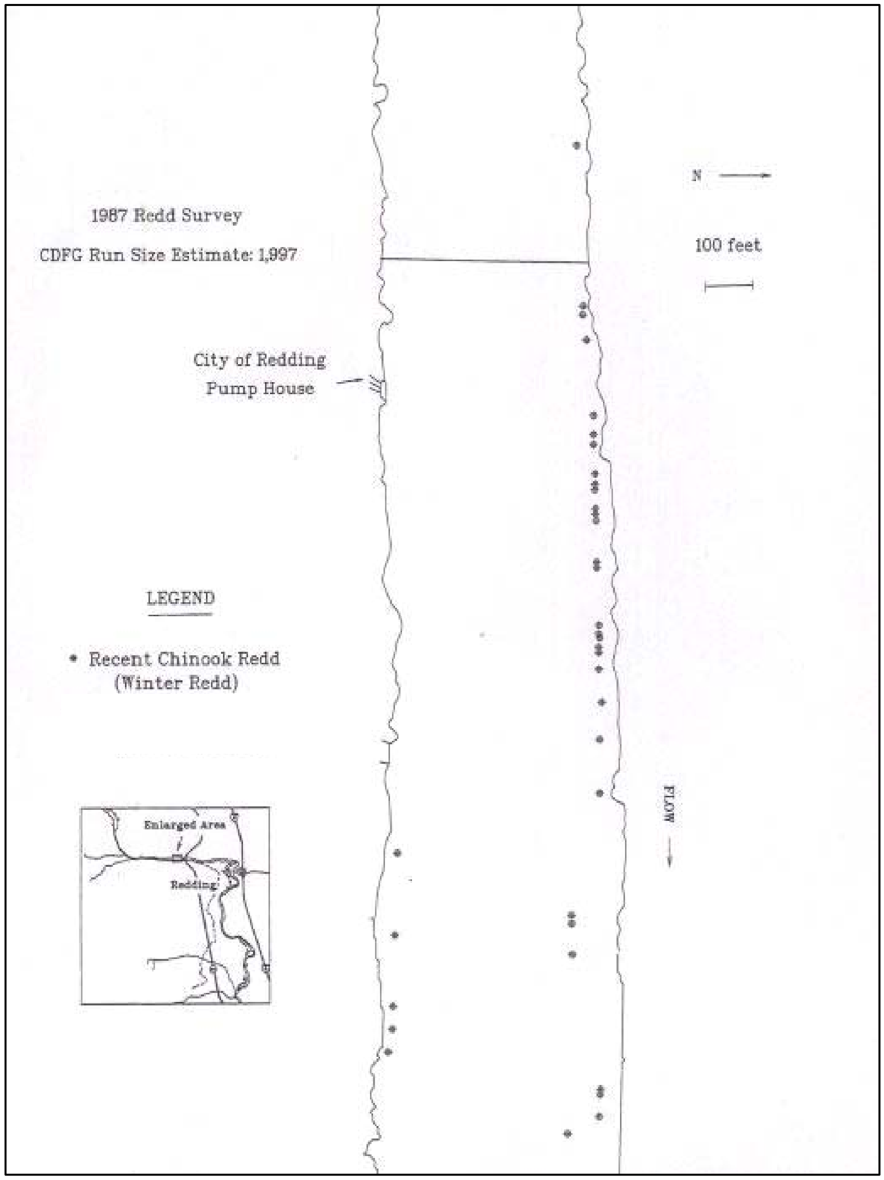


Figure 20. Winter-run Chinook salmon redds in the Sacramento River upstream of Dieselhorst Bridge (RM 299.0–299.3) in 1987. Source: Bigelow 1996.

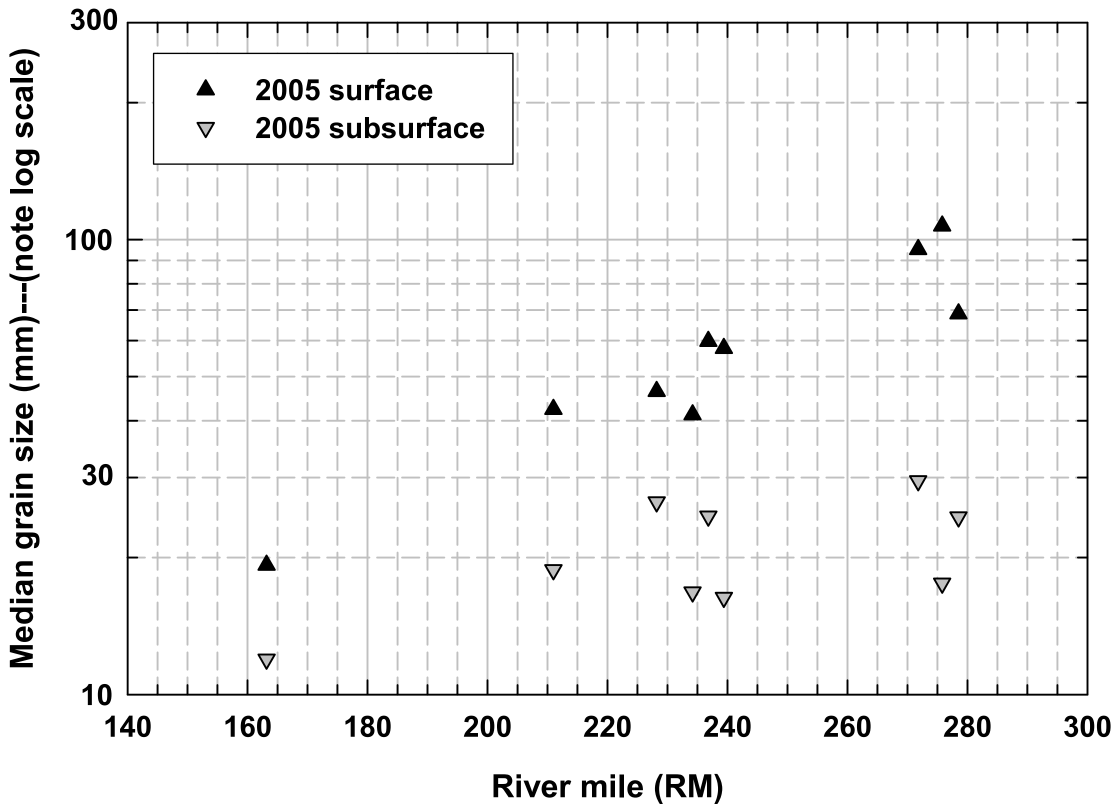


Figure 21. Median grain size as a function of river mile for heads of point bars (at riffles) in 2005, as determined from bulk samples. Median grain sizes of both the surface and subsurface decline, on average, with distance downstream.

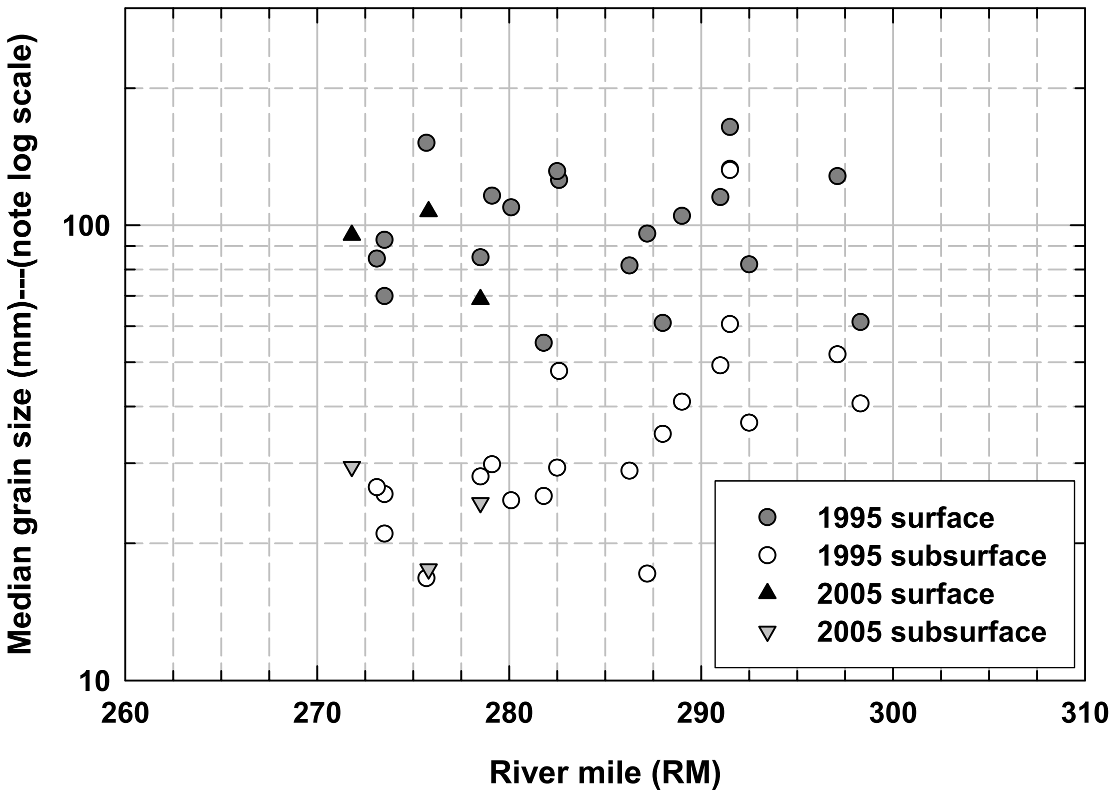


Figure 22. Median grain size in the upper river as a function of river mile for heads of point bars (at riffles) in 1995 and 2005, as determined from bulk samples. The methods used in 1995 and 2005 were similar: samples were of comparable size, and were collected from 2.4-2.7 m^2 (8-9 ft^2) surfaces that were selected randomly from point bars in the river near the water's edge. The data are consistent with essentially no change in median grain size over time. This interpretation is limited by the fact that data from 2005 only partly overlap in extent with data from 1995 (i.e., from RM 270 to RM 280).

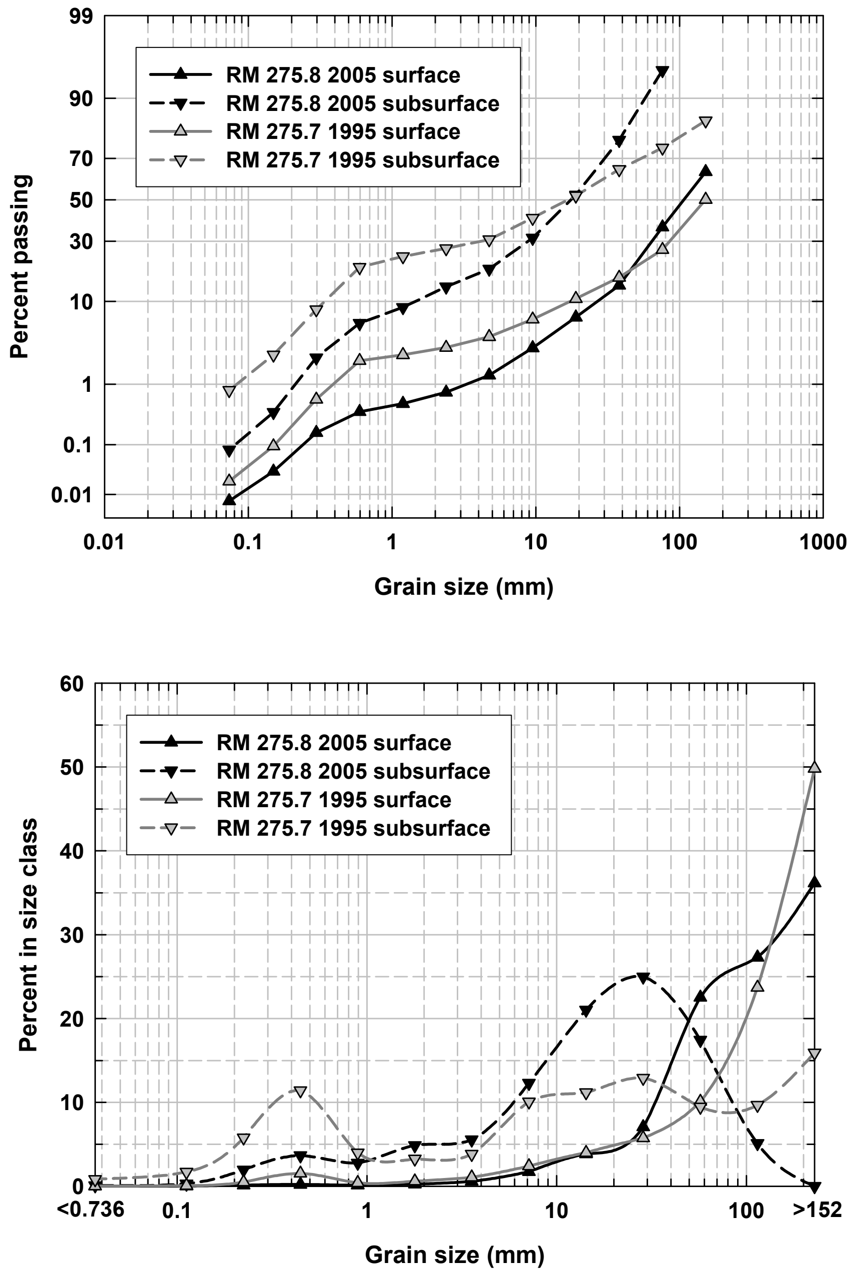


Figure 23. Time series of grain-size cumulative distribution functions (A) and probability distribution functions (B) of the surface (up-pointing triangles, solid line) and subsurface (down-pointing triangles, dashed line) at geomorphically comparable positions on a point bar at RM 275.7, based on data from bulk samples.

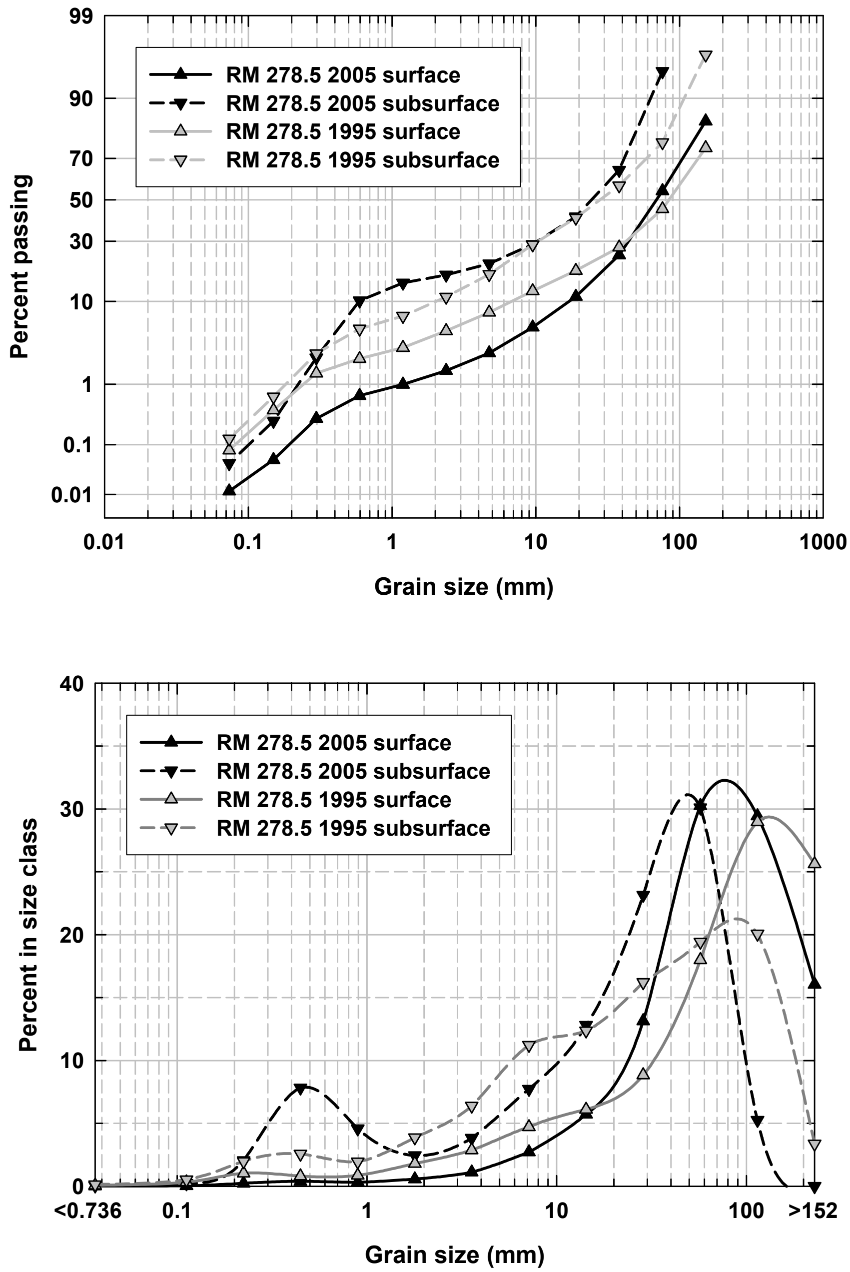


Figure 24. Time series of grain-size cumulative distribution functions (A) and probability distribution functions (B) of the surface (up-pointing triangles, solid line) and subsurface (down-pointing triangles, dashed line) at geomorphically comparable positions on a point bar at RM 278.5, based on data from bulk samples.

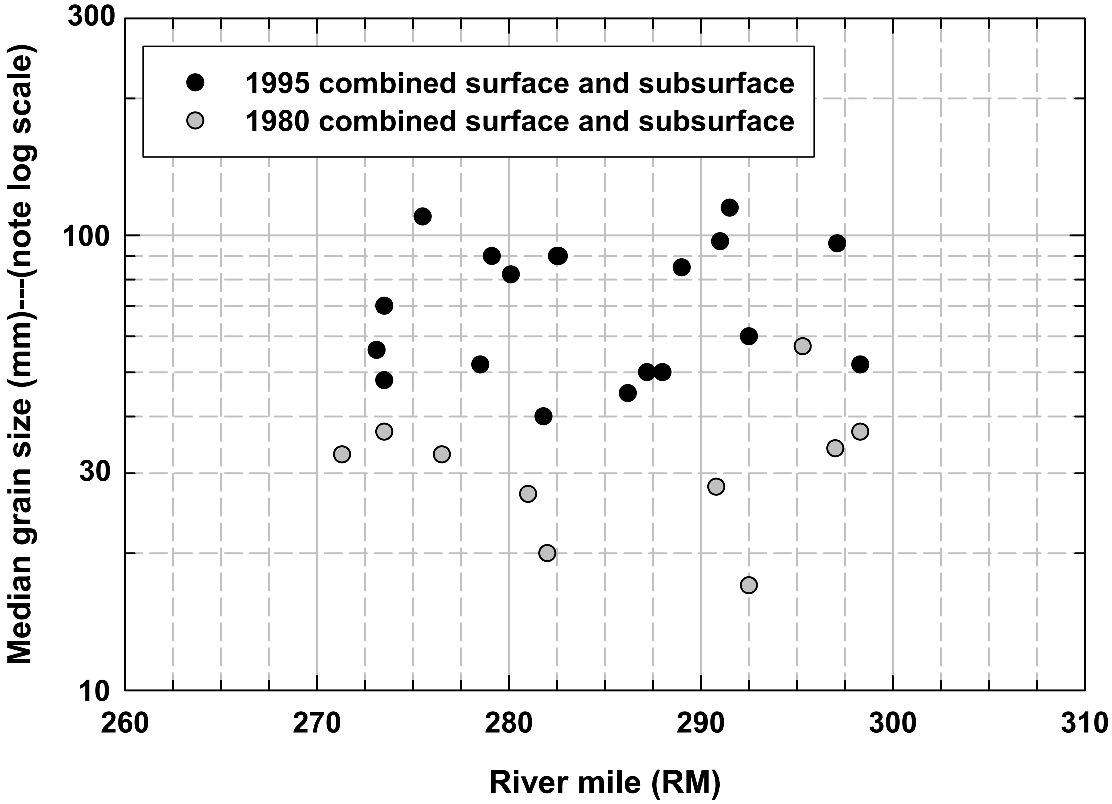


Figure 25. Median grain size (determined from bulk samples) as a function of river mile for heads of point bars (at riffles) in 1980 and 1995. A systematic offset seems to suggest that samples were coarser in 1995. But this conclusion is not actually supported by the data due to discrepancies in the sampling methods (see text). The differences in sampling methods can explain the observed pattern (apparently coarser samples in 1995) in the absence of an increase in grain size over time.

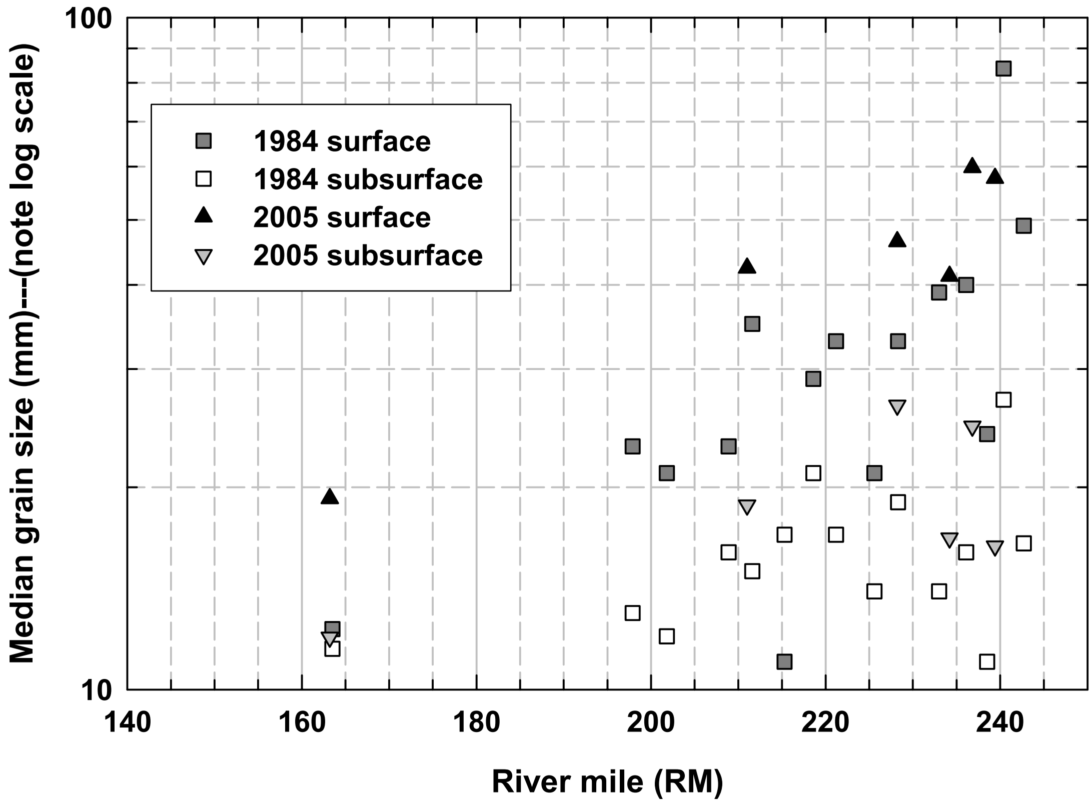


Figure 26. Median grain size in the middle river as a function of river mile for heads of point bars (at riffles) in 1984 and 2005, as determined from bulk samples. The slight offset in both the surface and subsurface samples seems to suggest that samples were coarser in 2005, but this conclusion is not supported by the data because differences in the sampling methods could produce the observed pattern in the absence of coarsening. The smaller sampling plot of the 1984 methodology (Buer 1984) may have biased the sampling toward relatively fine-grained sites, and moreover would have been unable to sample enough particles to make D_{50} statistically representative of the point bar. In contrast, in 2005 when larger plot was sampled, sample sizes were 2 or more times larger than they were in 1984. From a statistical standpoint, this would make the 2005 sampling more robust and less likely to be biased toward fine-grained sites.

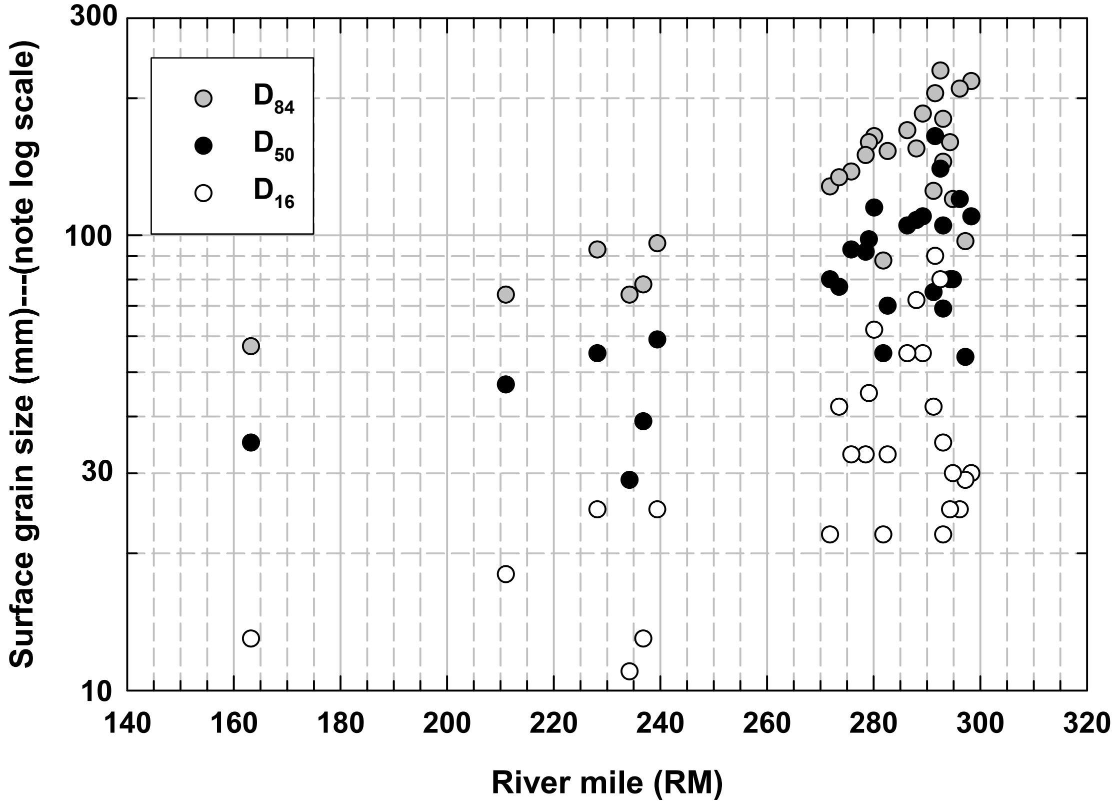


Figure 27. Grain size indexes (determined from Wolman counts) as a function of river mile for heads of point bars (at riffles) in 2005 (this study). Wide scatter within each data set is indicative of substantial natural variability in grain size at the local (i.e., few tens to hundreds of meters) scale.

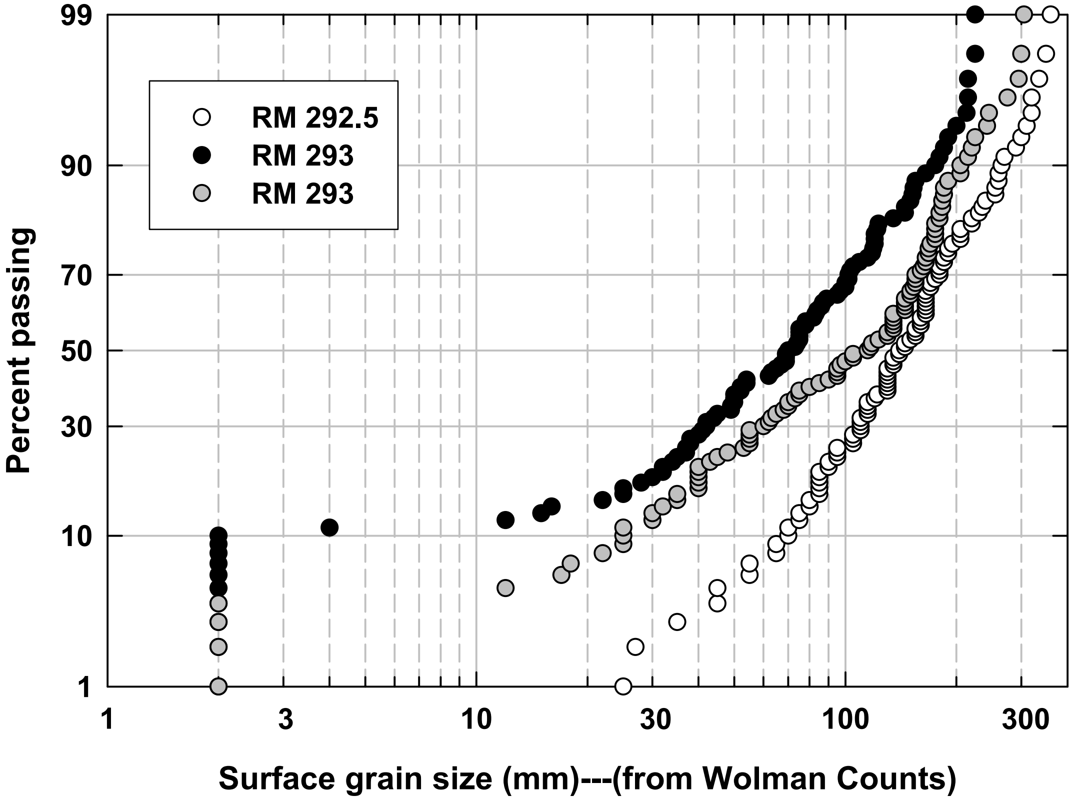


Figure 28. Grain-size distributions of the surface inferred from Wolman Counts at 3 locations on the Sacramento River in 2005. The Y axis shows a probability scale. Data show that grain size distributions vary substantially over the scale of a few hundred to one thousand meters.

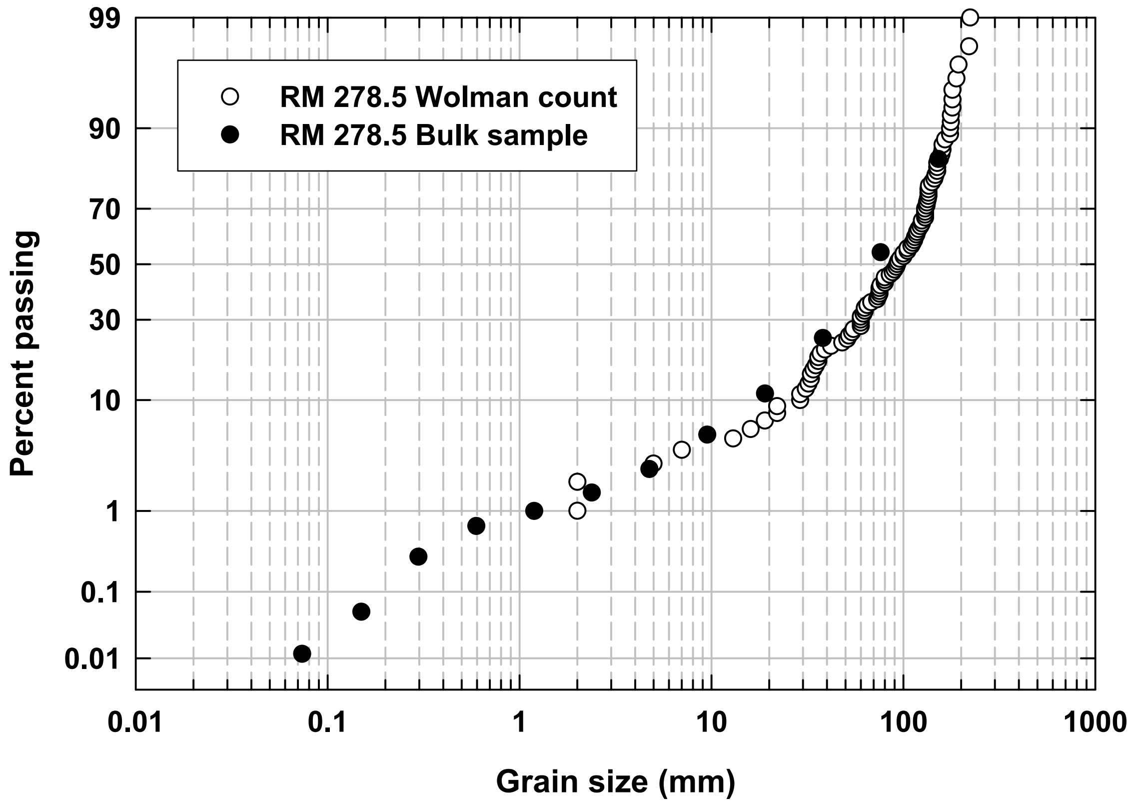


Figure 29. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.

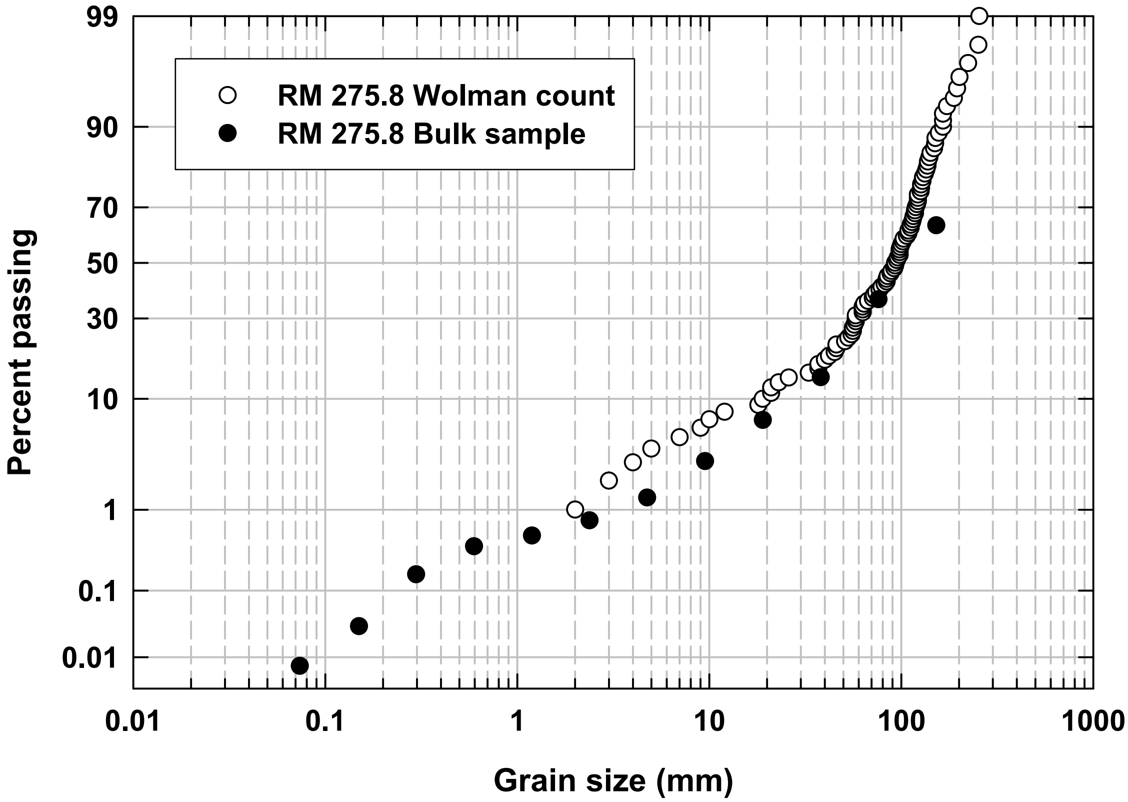


Figure 30. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.

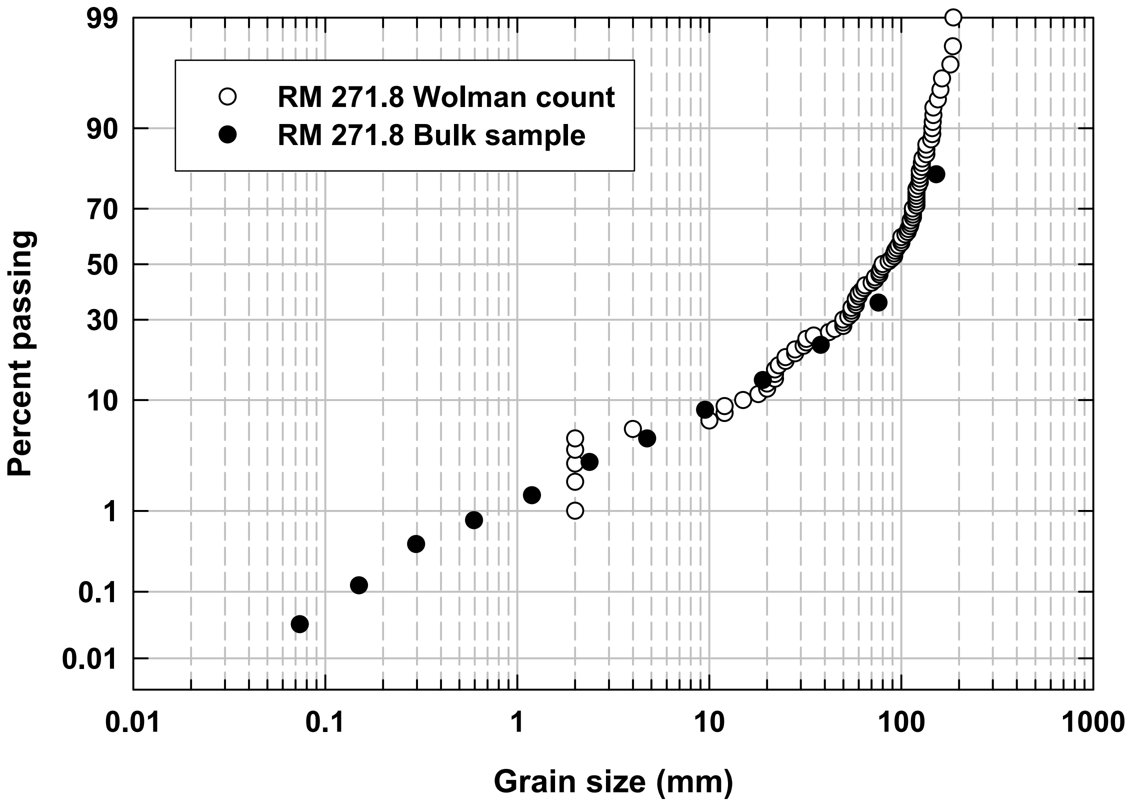


Figure 31. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.

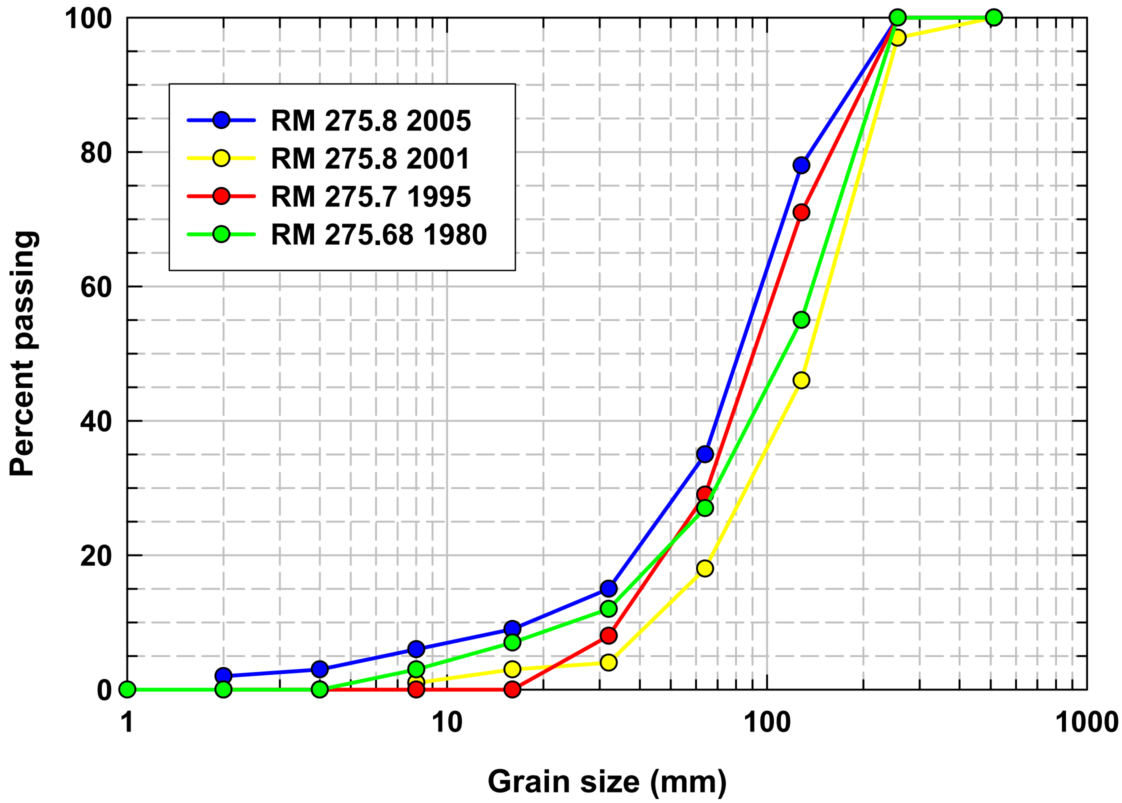


Figure 32. Time series of grain-size distributions from Wolman counts for a location on the upper river. Here, the grain-size measurements from 2005 are binned in "phi"-scale size classes for consistency with previous data. Data suggest the site became finer from 1980 to 1995, then significantly coarser by 2001, and was finer than ever by 2005.

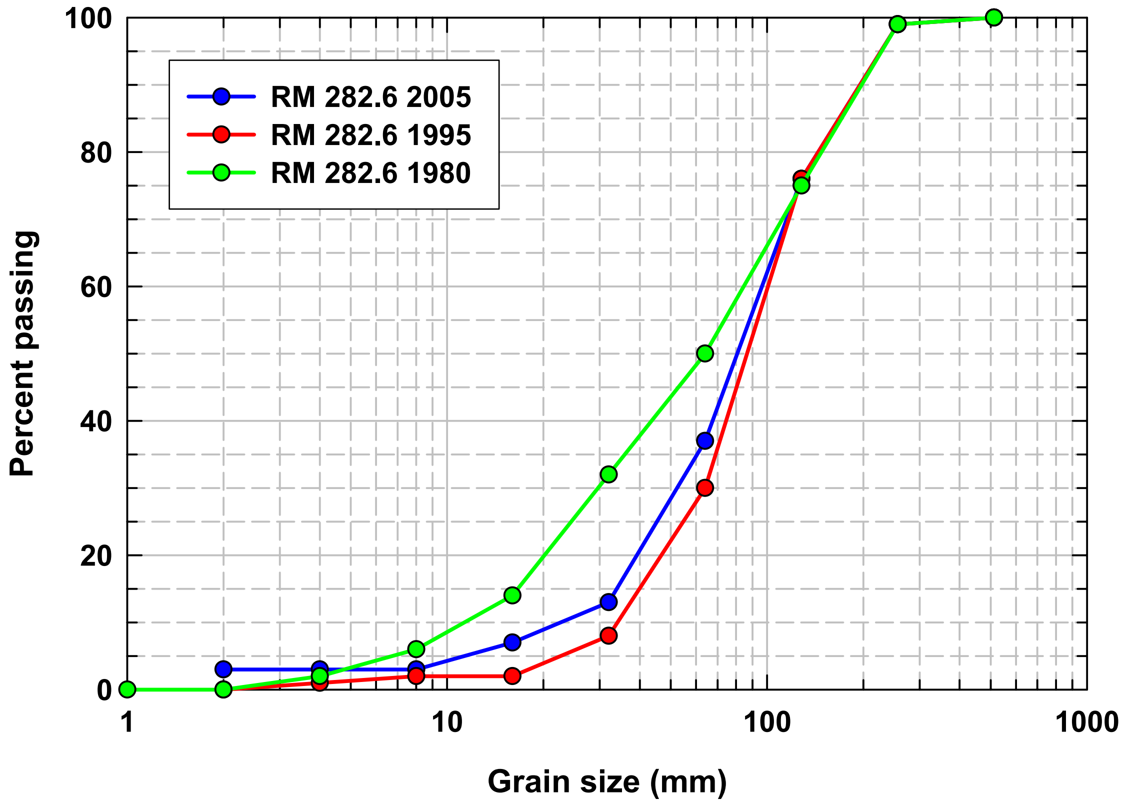


Figure 33. Time series of grain-size distributions from Wolman counts for a location on the upper river. Here, the grain-size measurements from 2005 are binned in "phi"-scale size classes for consistency with previous data. Data suggest the site became coarser by 1995 and then finer from 1995 to 2005.

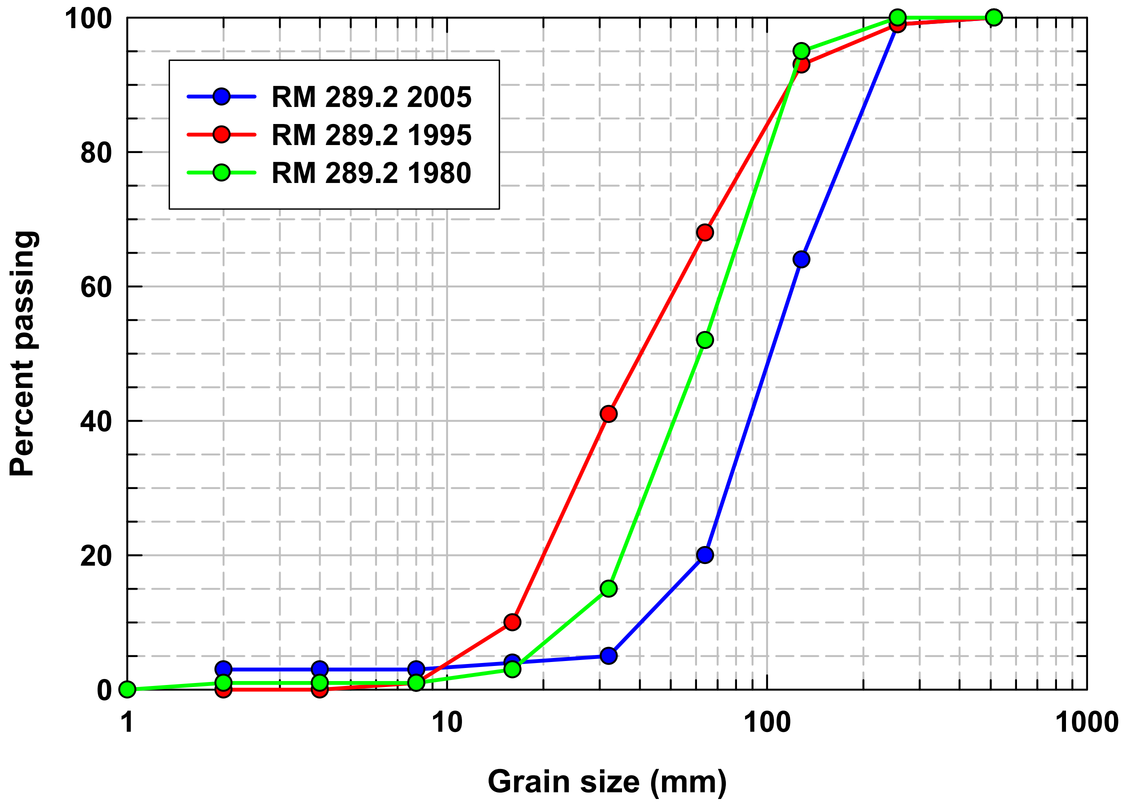


Figure 34. Time series of grain-size distributions from Wolman counts for a location on the upper river. Here, the grain-size measurements from 2005 are binned in "phi"-scale size classes for consistency with previous data. Data suggest the surface became finer by 1995 and then coarsened by 2005.

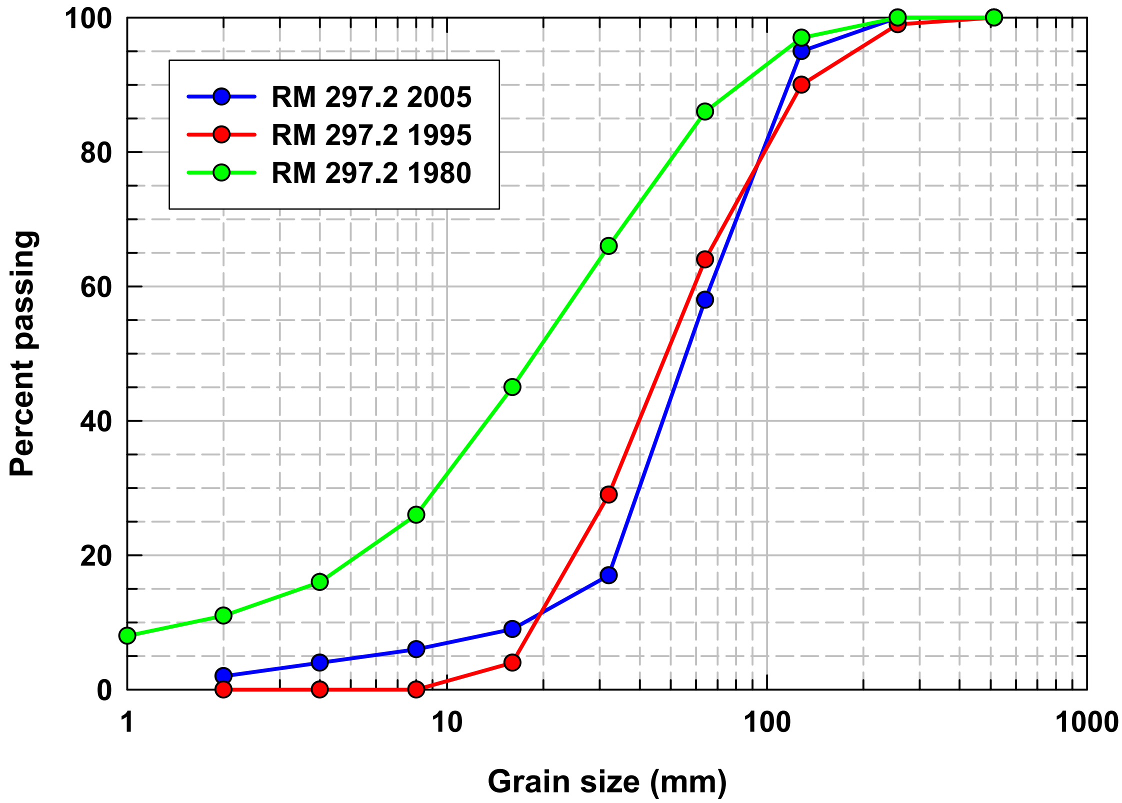


Figure 35. Time series of grain-size distributions from Wolman counts for a location on the upper river. Here, the grain-size measurements from 2005 are binned in "phi"-scale size classes for consistency with previous data. Data suggest the surface became significantly coarser by 2005.

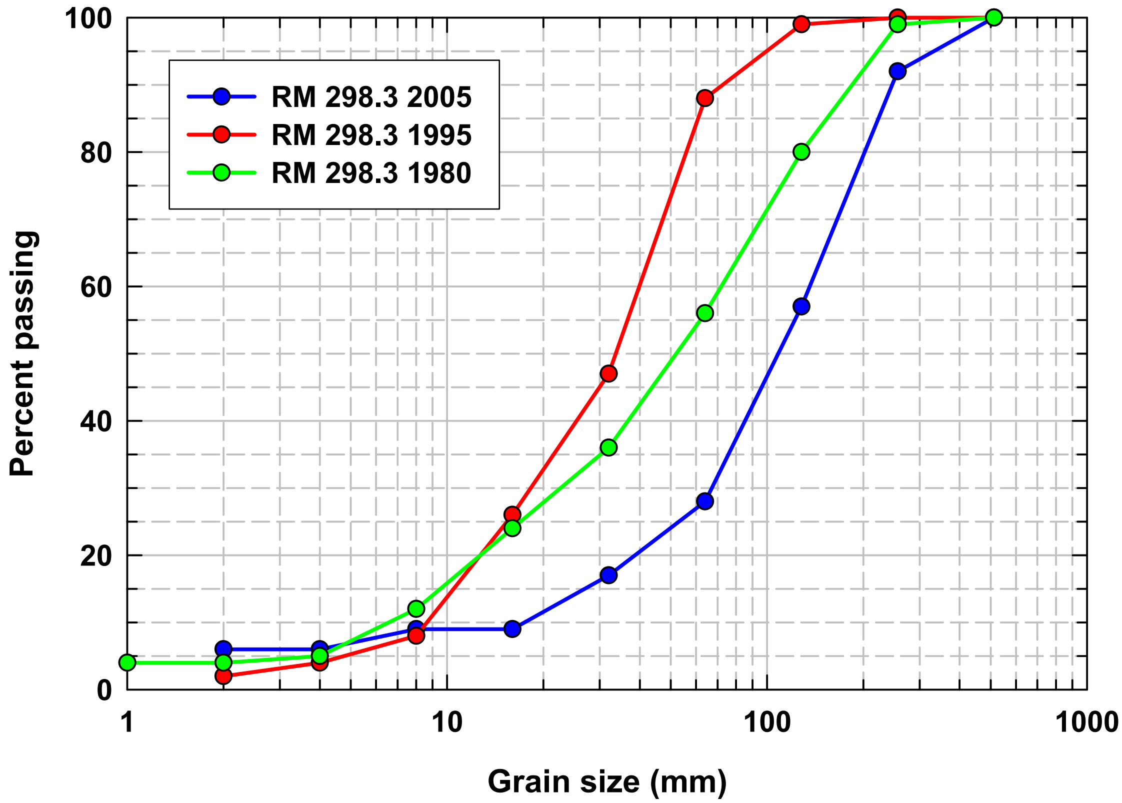


Figure 36. Time series of grain-size distributions from Wolman counts for a location on the upper river. Here, the grain-size measurements from 2005 are binned in "phi"-scale size classes for consistency with previous data. Data suggest the surface became finer by 1995 and then coarsened by 2005.

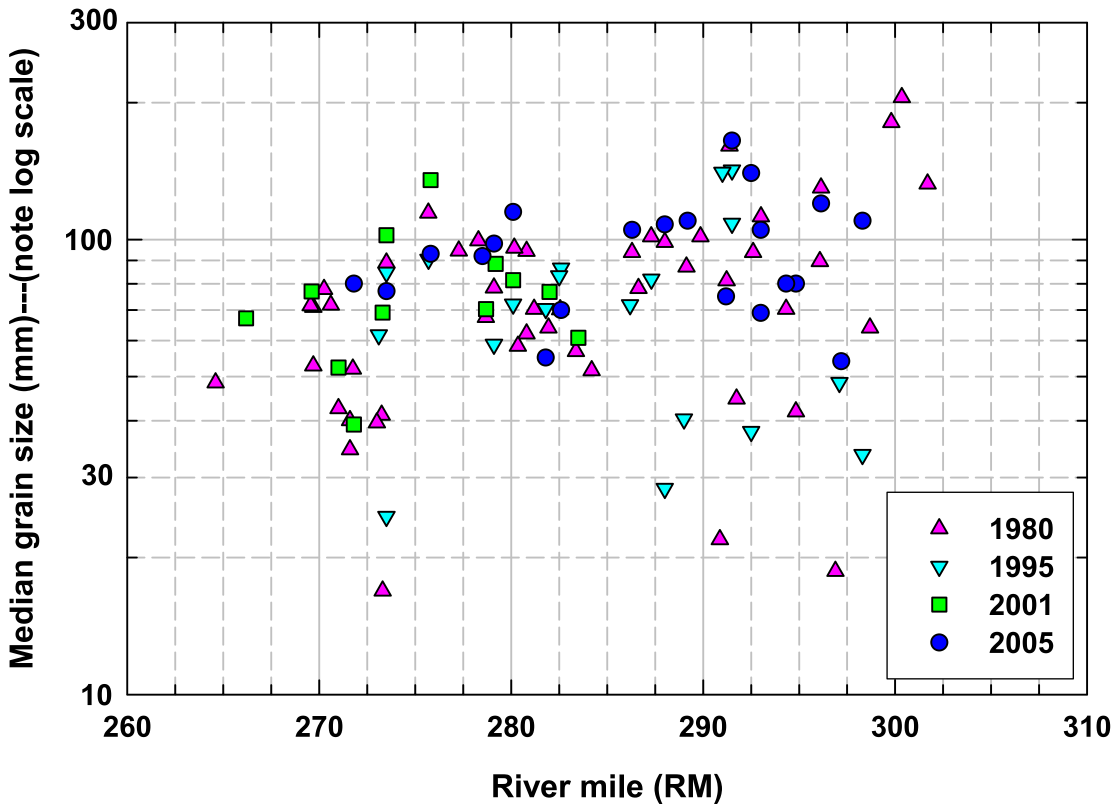


Figure 37. Median grain size on the upper Sacramento River (RM 310–260), based on Wolman pebble counts from geomorphically comparable positions on point bars. A time series of median grain sizes as a function of river mile shows wide scatter within each data set, indicating there is substantial natural variability in grain size at the local (ten- to hundred-meter) scale. Data from later years fall entirely within the range plotted by the earliest data set from 1980. The upper limits on median grain size are essentially constant, indicating that the coarsest deposits have not become substantially coarser (or finer) over the sampling interval. In contrast, the lower limits on median grain size appear to have changed over time, such that it has become increasingly less likely to sample riffles with relatively low median grain sizes (note the absence of data below about 50 mm as of 2001 and 2005). This is broadly consistent with hypothesis 1—the finest riffles appear to have been coarsening over time in the upper river over the last 25 years. A formal, statistical analysis confirms the visual impressions of this plot (see text).

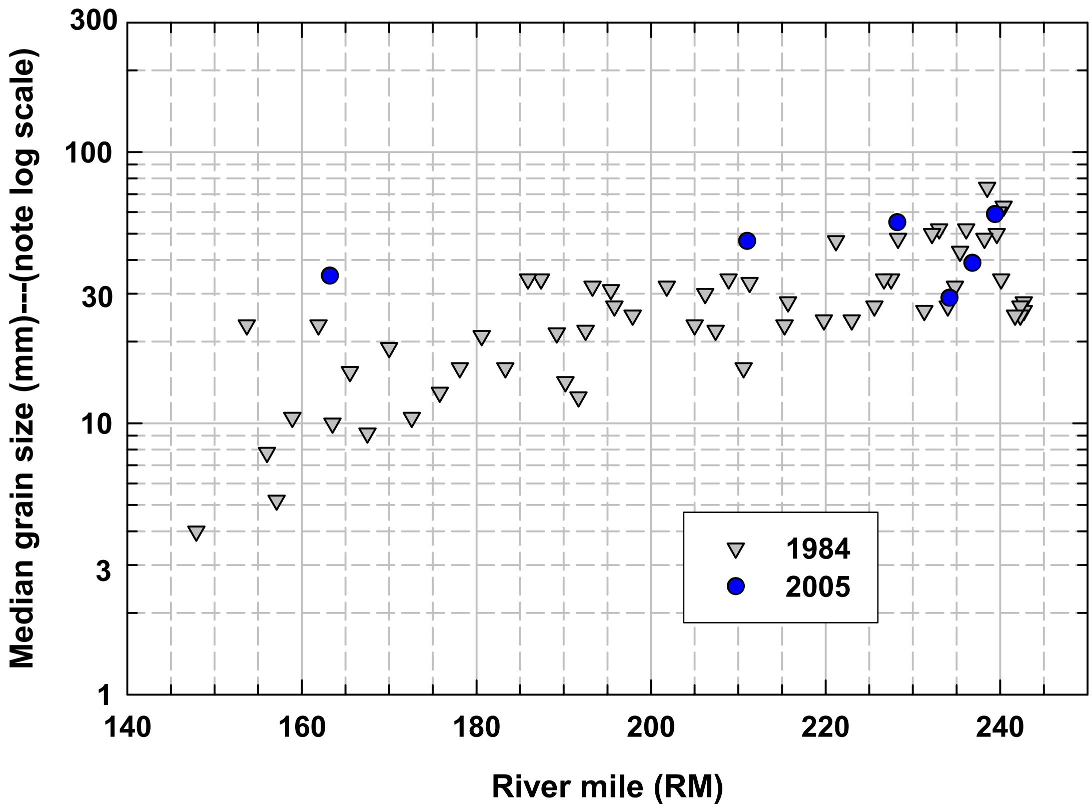


Figure 38. Time series of median grain sizes (determined from Wolman counts) as a function of river mile in the middle river for geomorphically comparable positions on point bars. The wide scatter within the 1984 data set is consistent with substantial (i.e., 3- to 5-fold) natural variability in grain size at the local (ten- to hundred-meter) scale. Overlap among data from the two periods is consistent with little change in median grain size over time; the fact that the grain sizes from 2005 at RM 163 and RM 211 plot somewhat higher than the band of data from 1984 is too isolated to support conclusions about systematic changes in grain size over time.

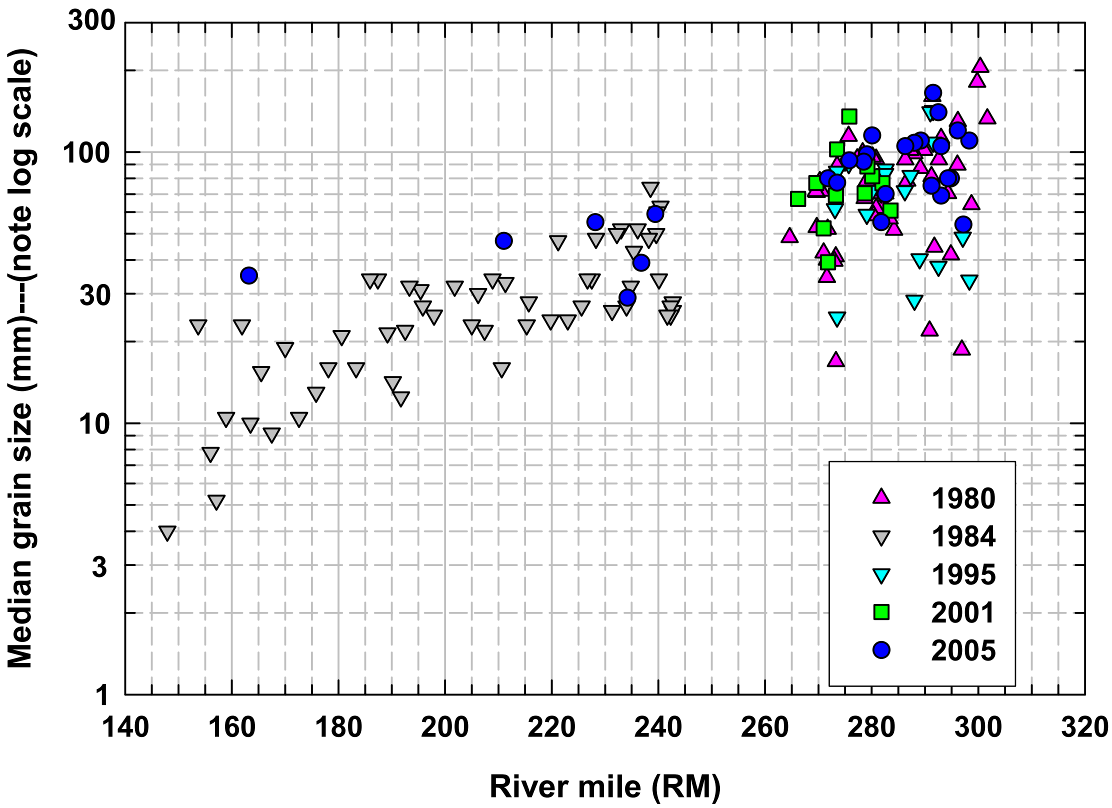


Figure 39. Time series of median grain sizes (determined from Wolman counts) as a function of river mile for geomorphically comparable positions on point bars across the entire study area. Data from Figure 37 and Figure 38 are compiled here for an overall view of grain size versus river mile at the different sampling times.

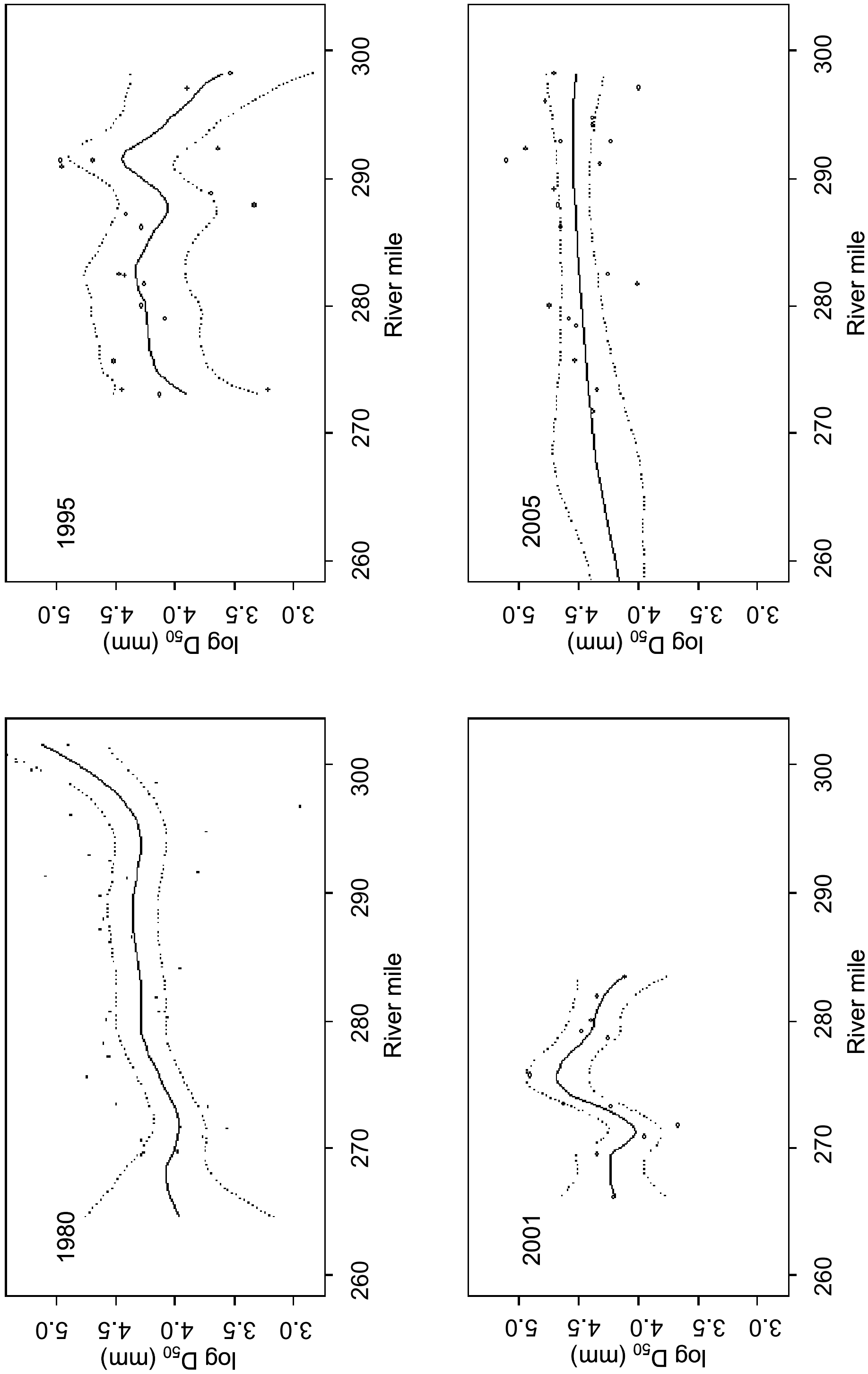


Figure 40. Median grain sizes (determined from Wolman counts) as a function of river mile at 4 points in time. Slopes (solid lines) and 95% confidence intervals (dashed lines) show best fits from the non-parametric regression analysis (see text). Data are derived from geomorphically comparable positions on point bars across the upper study area.

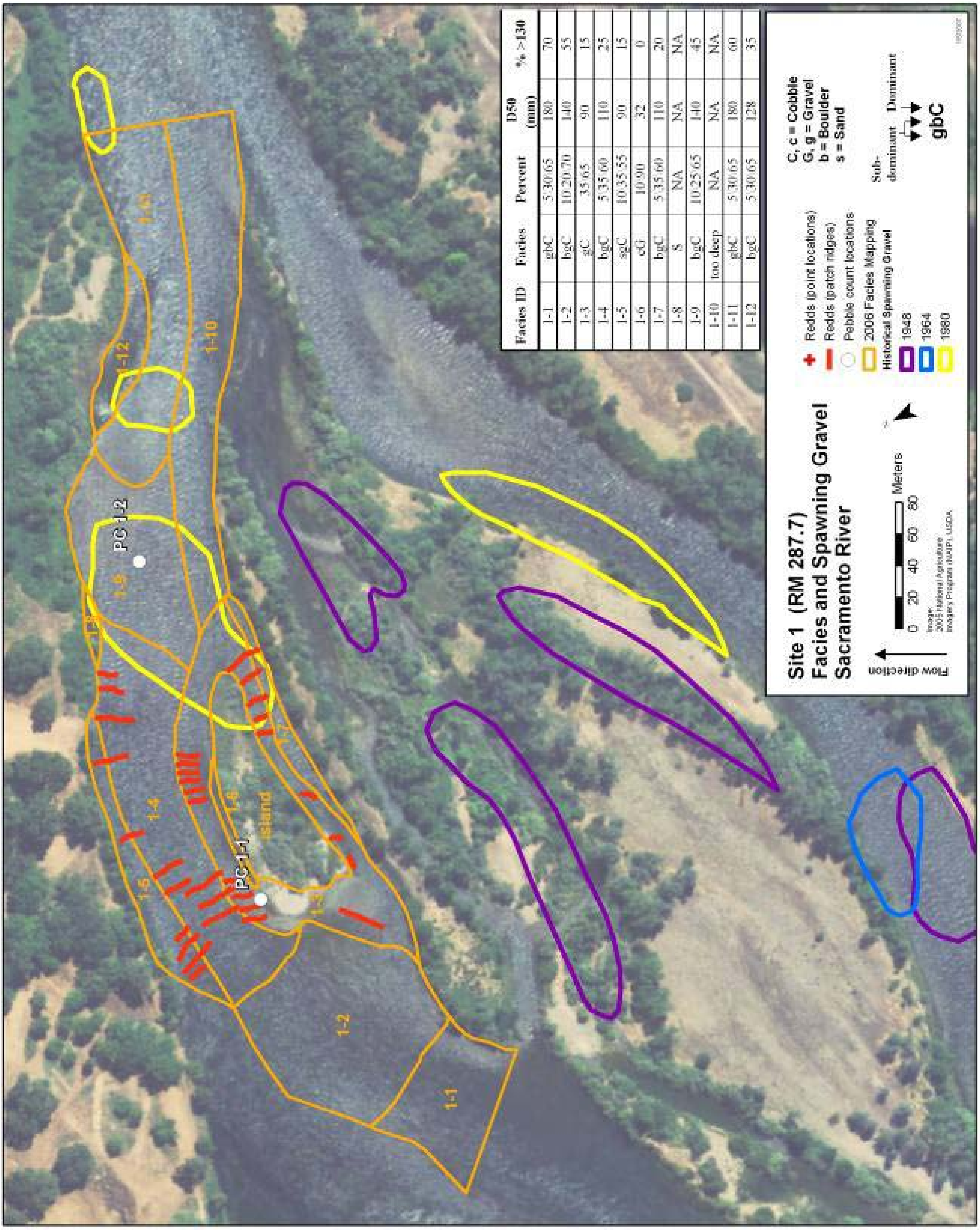


Figure 41. Facies map site 1 at RM 287.7.

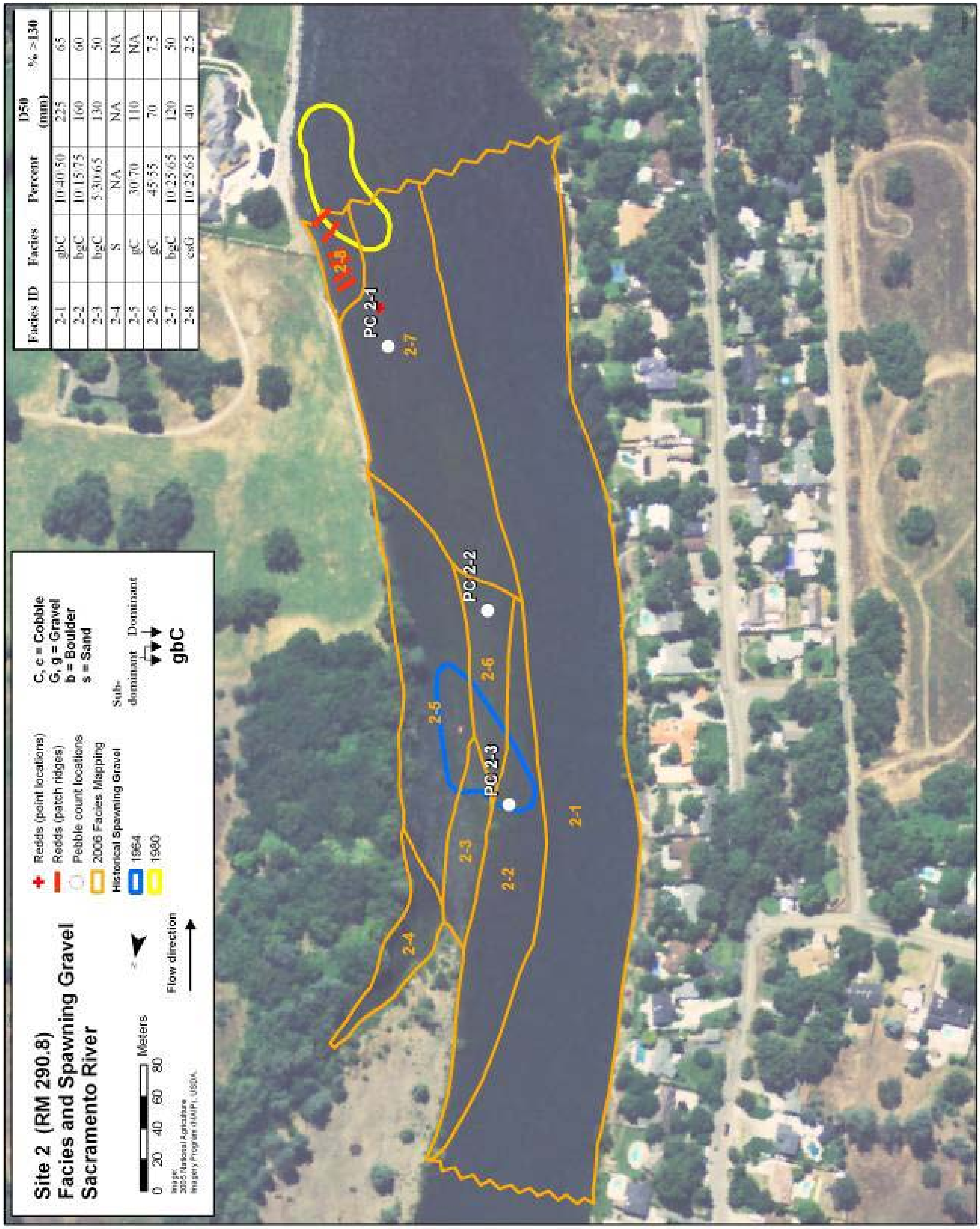
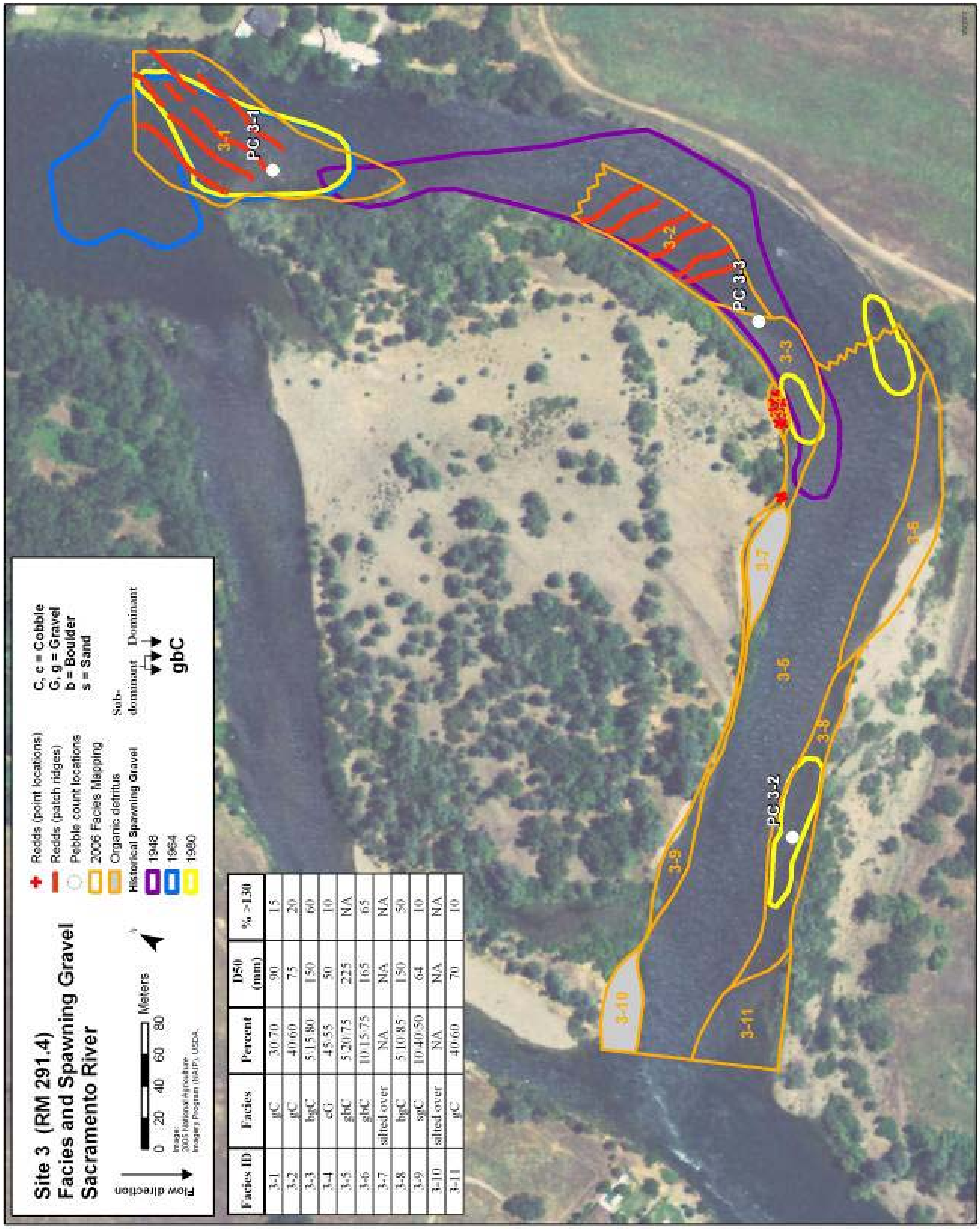


Figure 42. Facies map site 2 at RM 290.8.



Facies ID	Facies	Percent	D50 (mm)	% >130
3-1	gC	30/70	90	15
3-2	gC	40/60	75	20
3-3	bgC	5/15/80	150	60
3-4	cG	45/55	50	10
3-5	gbC	5/20/75	225	NA
3-6	gbC	10/15/75	165	65
3-7	silted over	NA	NA	NA
3-8	bgC	5/10/85	150	50
3-9	sgC	10/40/50	64	10
3-10	silted over	NA	NA	NA
3-11	gC	40/60	70	10

Figure 43. Facies map site 3 at RM 291.4.

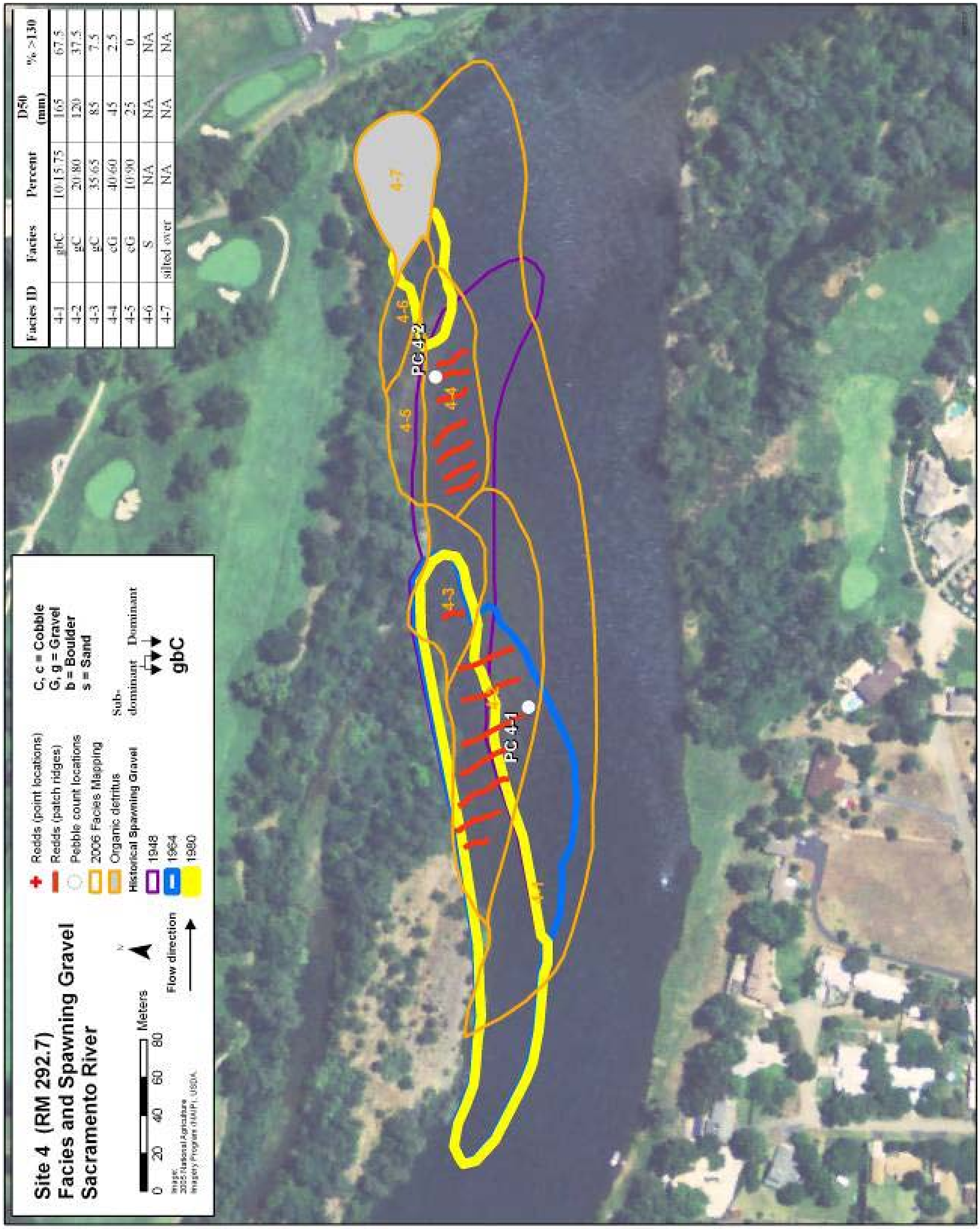


Figure 44. Facies map site 4 at RM 292.7.

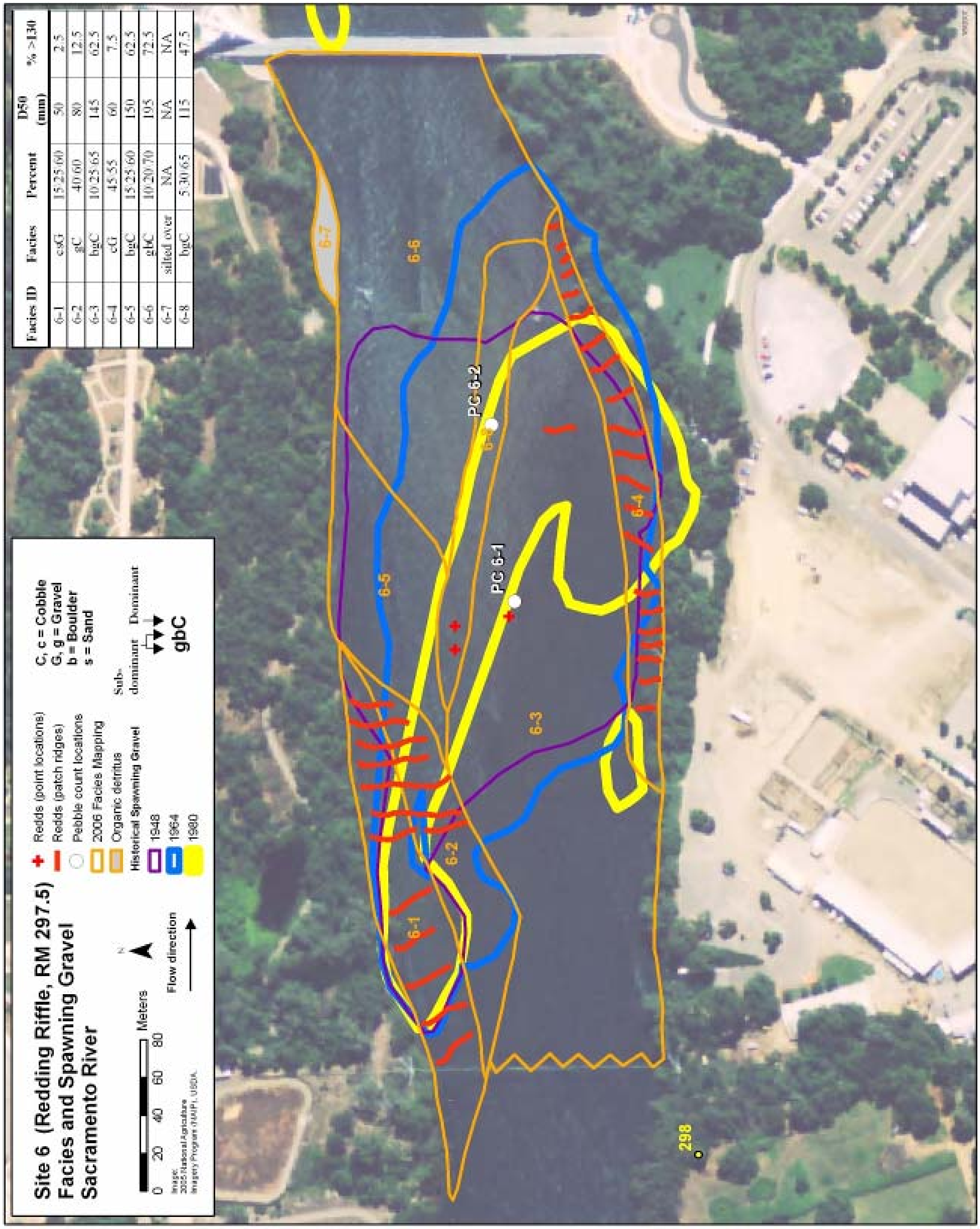


Figure 45. Facies map site 6 at RM 297.5.

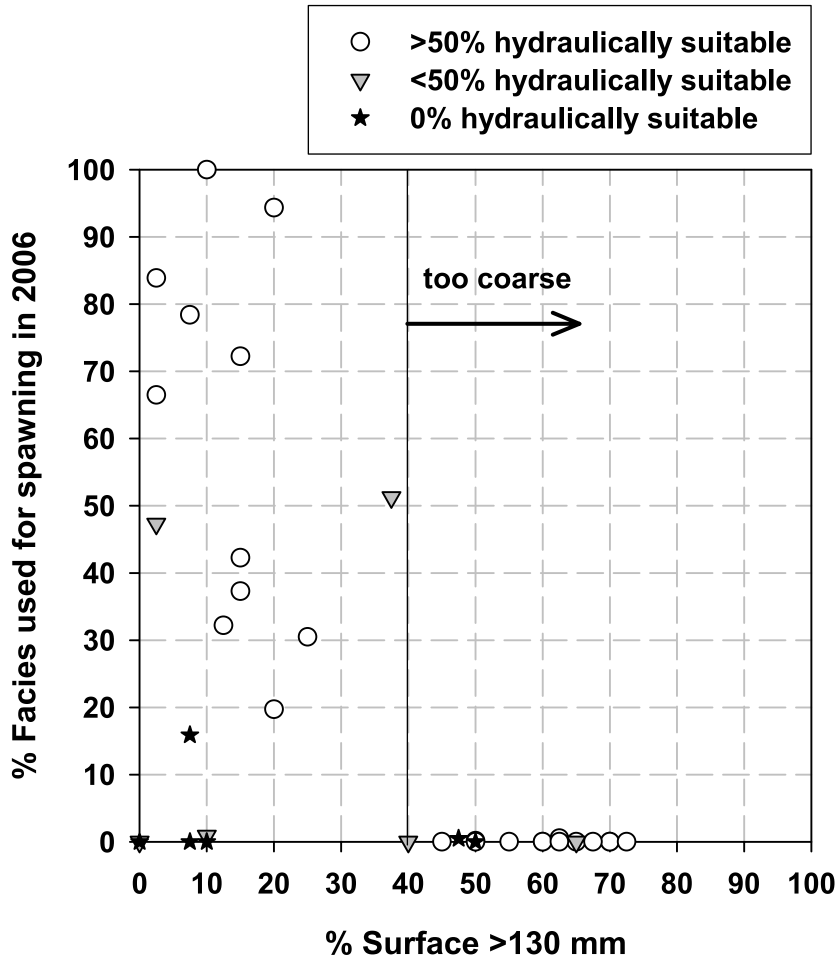


Figure 46. Percent of area used by spawning fish in 2006 against the percent coverage by particles with intermediate axis diameters >130 mm for each of the facies on the Sacramento River. Hydraulic conditions were judged to be mostly favorable for spawning in only some of the facies (plotted as open circles) at the time of the field work. Spawning was scarce or absent in facies where <50% of the area was hydraulically suitable (plotted as triangles for 1-50% and stars for 0%). Spawning was also absent in areas with more than 40% coverage by particles with b-axis diameters >130 mm. We suggest that the 40% level of coarse particles represents an upper threshold on spawning suitability.

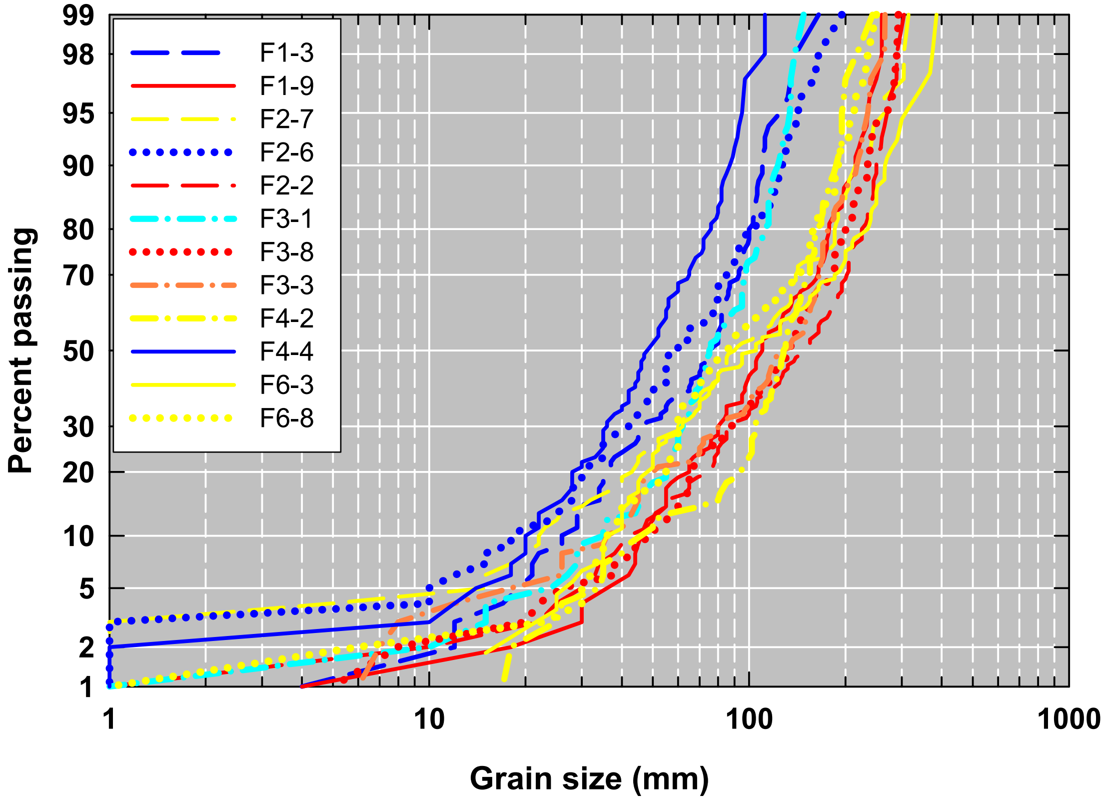


Figure 47. Grain-size distributions of the surface inferred from Wolman counts from 12 facies (labeled in the legend) of the Sacramento River gravel study. The Y axis is a probability scale. Blue lines are distributions from sites with active spawning at the time of the mapping (F1-3, F3-1, and F4-4), or suitable grain size characteristics and a lack of spawning due to poor hydraulic conditions (F2-6). Red lines are distributions from areas where evidence of spawning was absent despite apparently suitable hydraulic conditions. Yellow lines are distributions from the edges of active spawning areas and areas where marginal spawning and potentially failed redds were observed. These distributions presumably characterize gravel near the threshold of spawning suitability, and with the exception of the one from F4-2 show a mixture of seemingly suitable median grain sizes and coarse tails that overlap with unsuitable conditions.

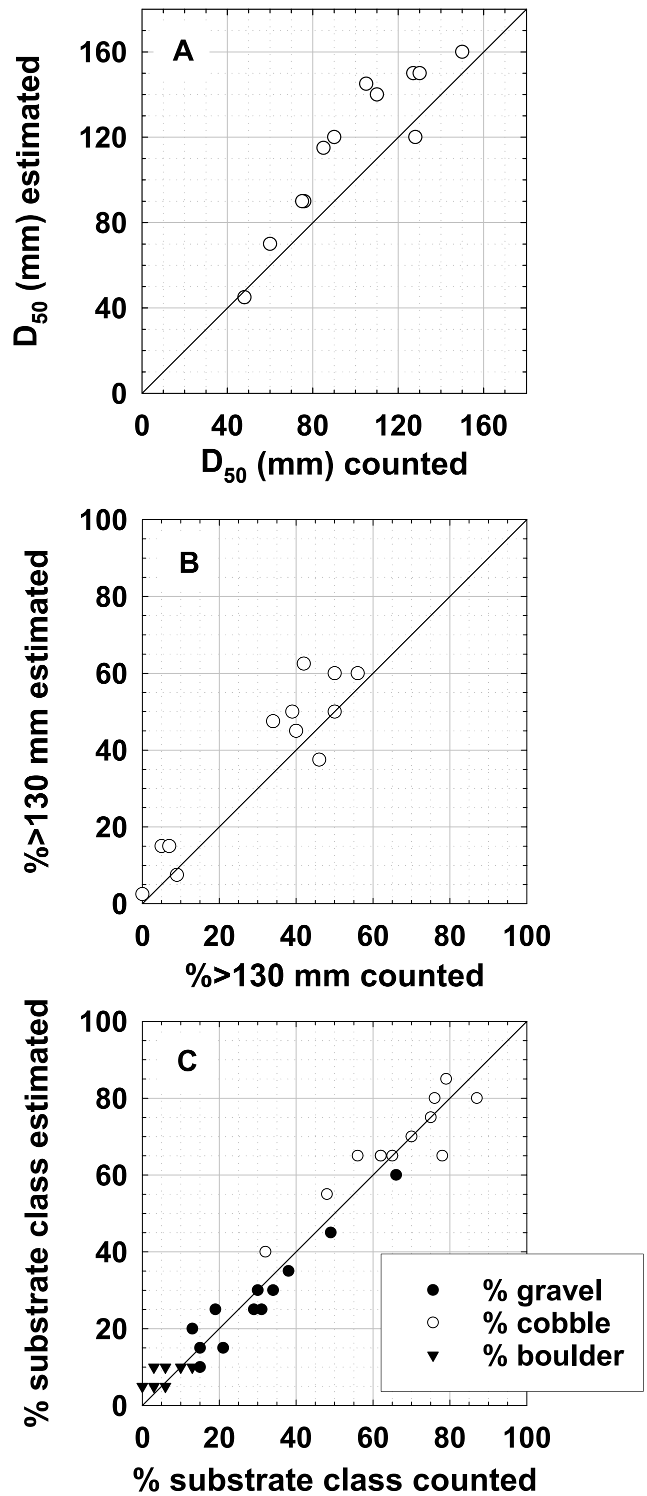


Figure 48. Comparison of estimated (vertical axes) and measured (horizontal axes) median particle size (A), percent coverage by particles with intermediate diameters >130 mm (B), and percent occurrence of each qualifying substrate class (C). Lines mark perfect agreement between estimated and measured values. Estimates of D_{50} were systematically high but generally within ± 20% of the measured value. Errors in estimated coverage by coarse particles and individual substrate types were typically less than 20% and 10%, respectively.

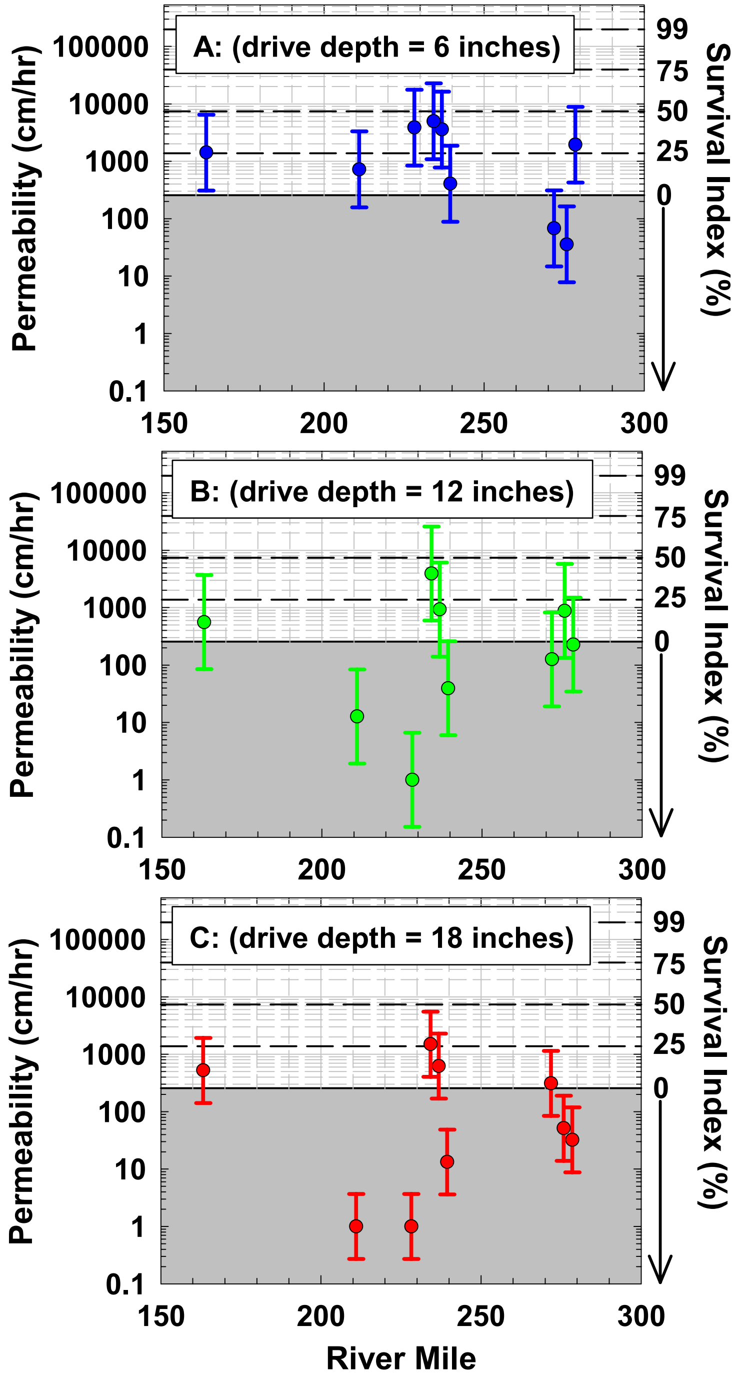


Figure 49. Permeability (left axis) and estimated survival index (right axis) in 2005 at 6 inches (A), 12 inches (B), and 18 inches (C) as a function of river mile for the middle and upper reaches of the Sacramento River. Data collected in 2006 and after "redd building" were excluded from the plots (see text). Permeability shows no clear trend with river mile for any of the drive depths. Survival index scaling and units (% survival) are based on available data for coho and Chinook salmon of the Pacific Northwest (see next figure). Shaded regions have estimated survival index equal to 0%. Low survival indices suggest that many of our sites would be unsuitable for successful spawning due to low permeability. This seems especially true at 12 and 18 inches (B and C), at depths where Sacramento River Chinook salmon are generally observed to bury their eggs. This highlights the likely importance of redd building as a mechanism for cleaning gravel (and thus enhancing its permeability) at spawning sites.

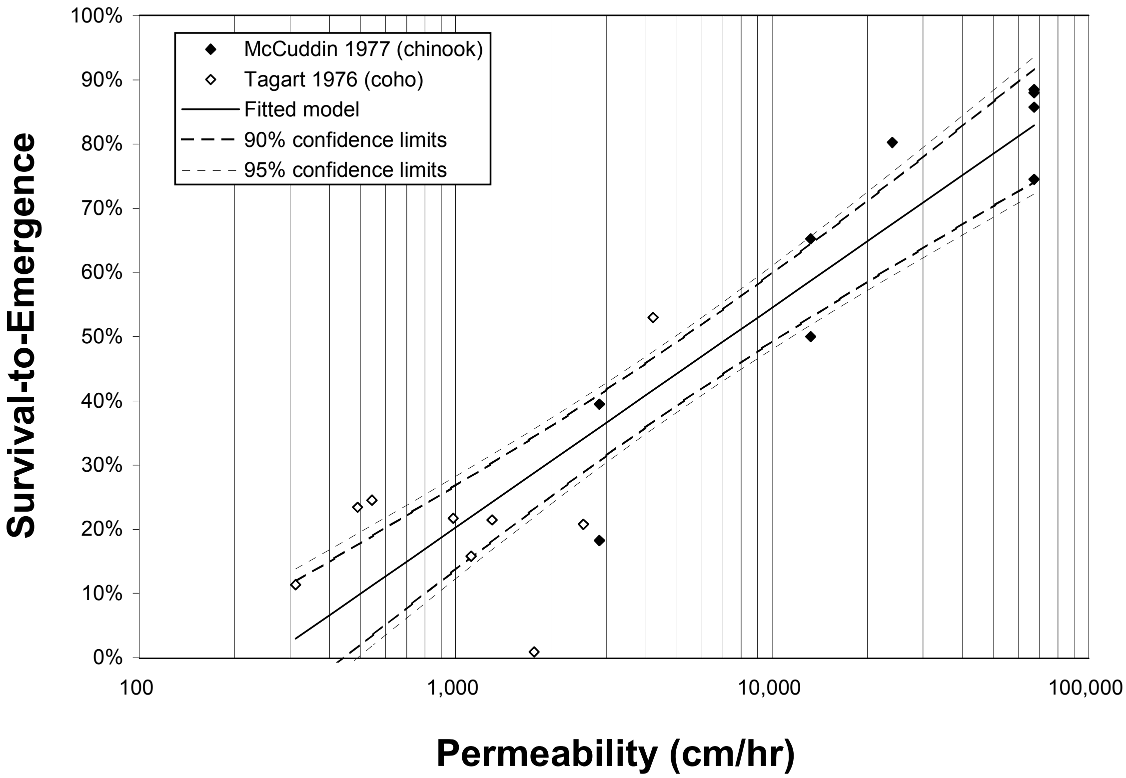


Figure 50. Measured survival to emergence (in %) plotted against the log of measured permeability for coho (Tagart 1976) and Chinook salmon (McCuddin 1977) of the Pacific Northwest, with best fit regression (see equation 1, text) and its 90- and 95-percent confidence limits.

Figure 51. Painted rock in one of 3 scour boxes at SW-6 (RM 271.7). Only a scant residue of paint remains on rocks in each box. This suggests that significant abrasion has worn it away during high flows. The fact that the rocks are still in the scour boxes, 20 m apart as they were the year before, nevertheless implies there has been minimal disruption of the bar surface.

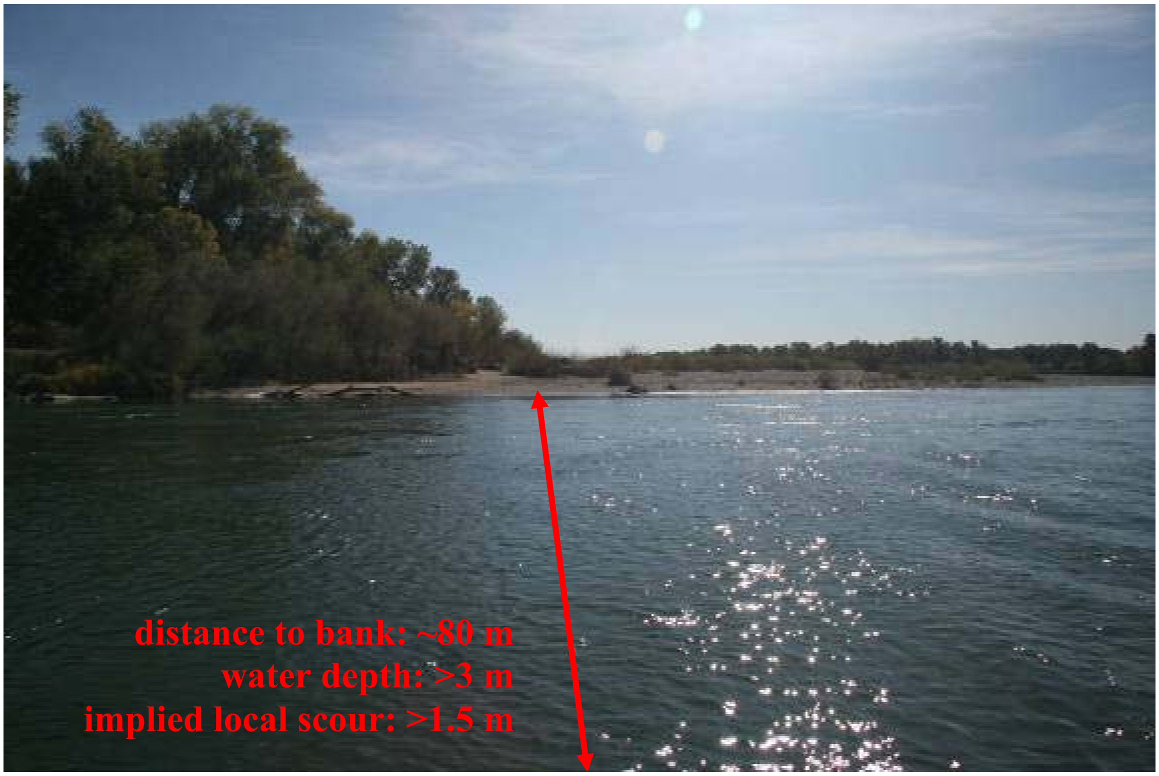


Figure 52. View of river bank from approximate site of scour chains at SW-3 (RM-236.8). Photo date: 10/26/2006. Water depth over the site was at least 3 meters and distance to the bank was 80 meters at the time of the photo. In contrast, scour chains were installed at the water's edge in 2005 under <0.5 meters of water. The difference in water depth and bank position from 2005 to 2006, despite similar flow conditions during installation and monitoring (see Table 15), implies that scour has been significant at the site. We estimate that at least 1.5 m of scour has occurred at SW-3. Other evidence at the site clearly points to widespread scour and lateral migration.

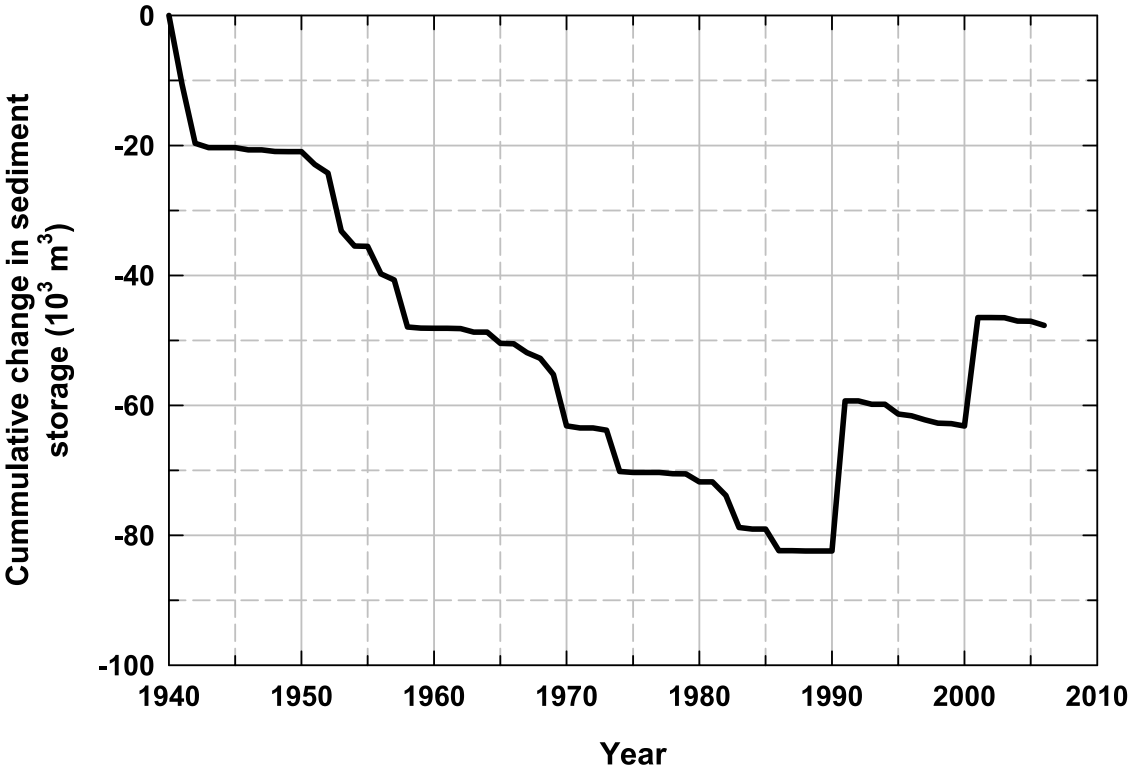


Figure 53. Simulated cumulative change in in-stream sediment storage in reach 3 (RM 295-290) in the post-dam era. After a sharp initial decline in sediment storage (due to the cessation of sediment supply from upstream sources), continued decreases in sediment storage were more progressive, and occurred in years with high flows. Gravel augmentation in 1990 and again in 2000 led to substantial one-time increases in sediment storage in the reach.

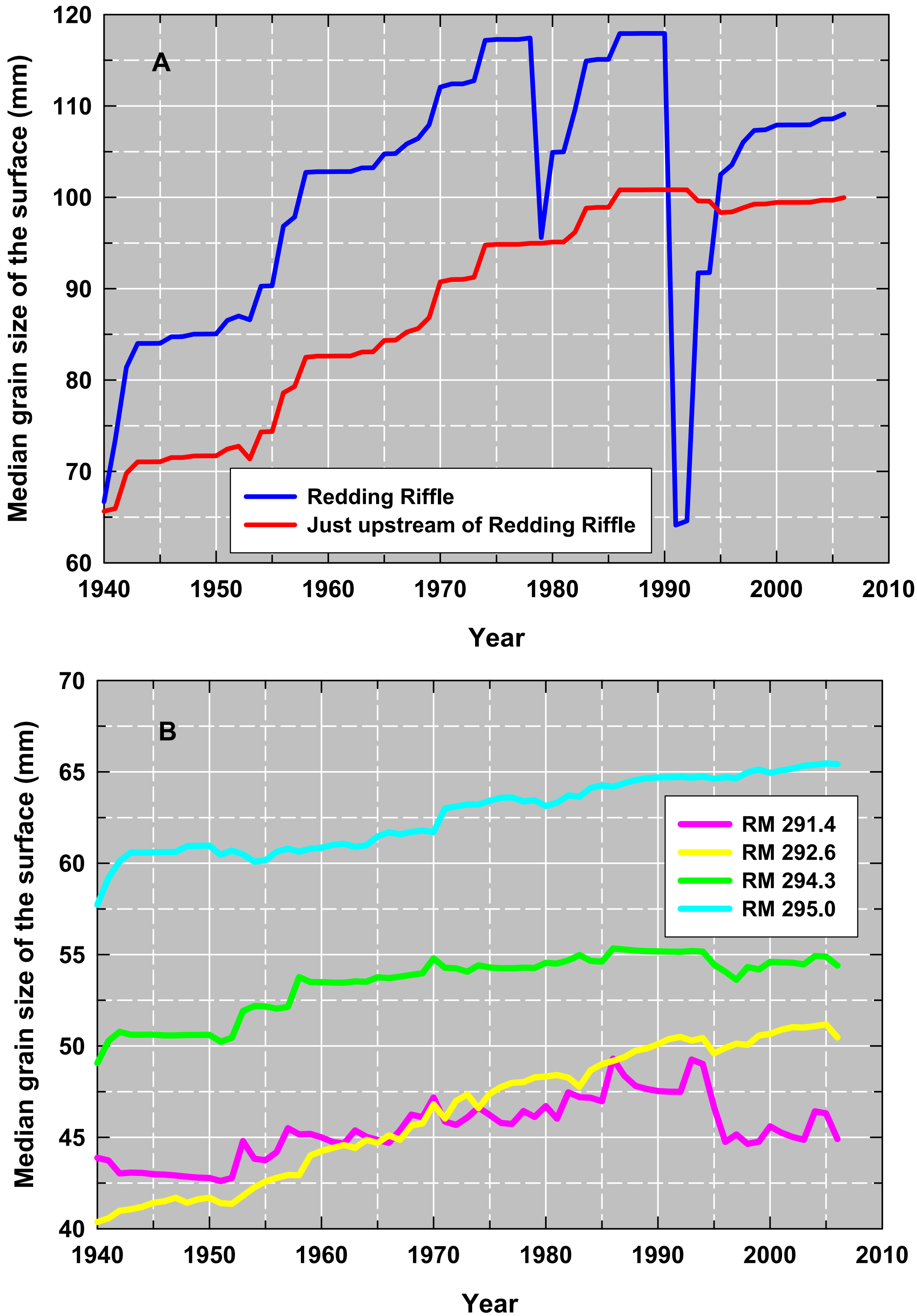


Figure 54. Simulated change in median grain-size of the surface at several sites in reach 2 (A) and reach 3 (b) of the sediment transport modeling analysis.

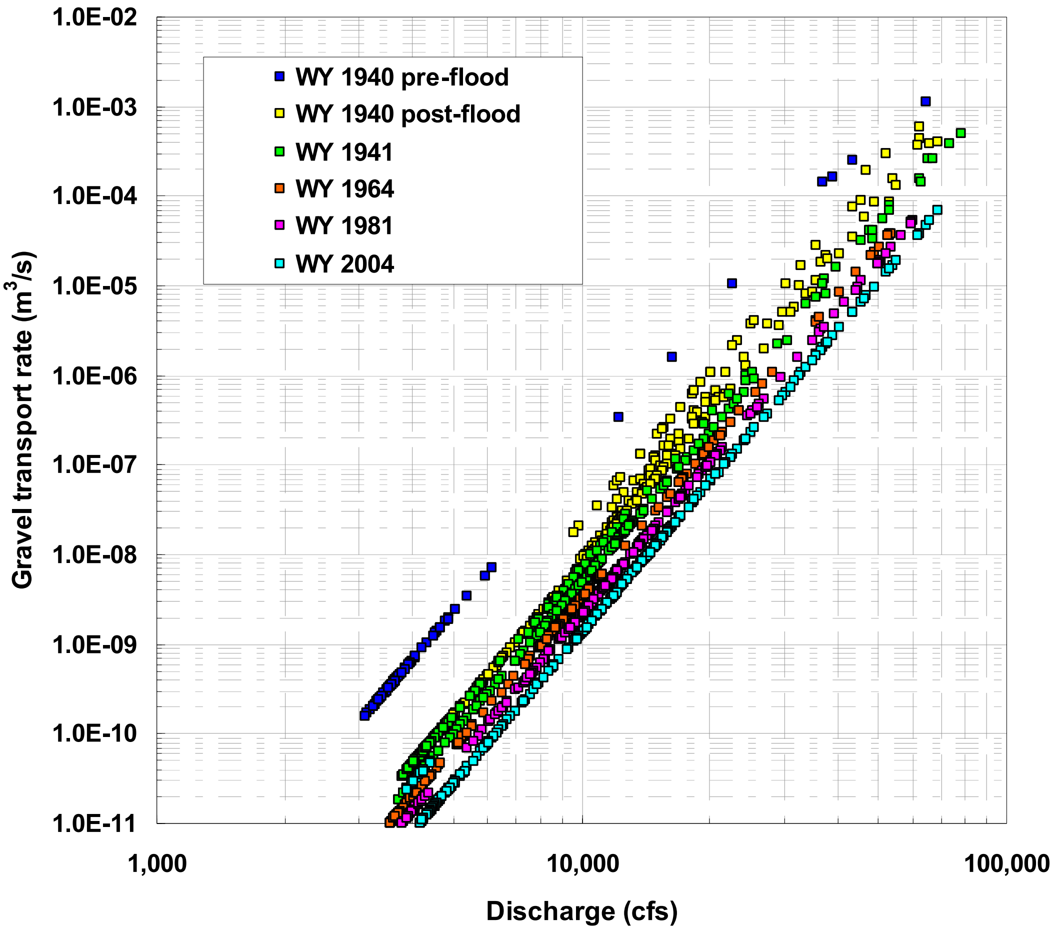


Figure 55. Sediment rating curves from TUGS model simulations at RM 294. The shift in the curves over time is a direct result of coarsening, which reduces bed mobility and thus reduces the predicted amount of sediment transport that should occur for a given flow.

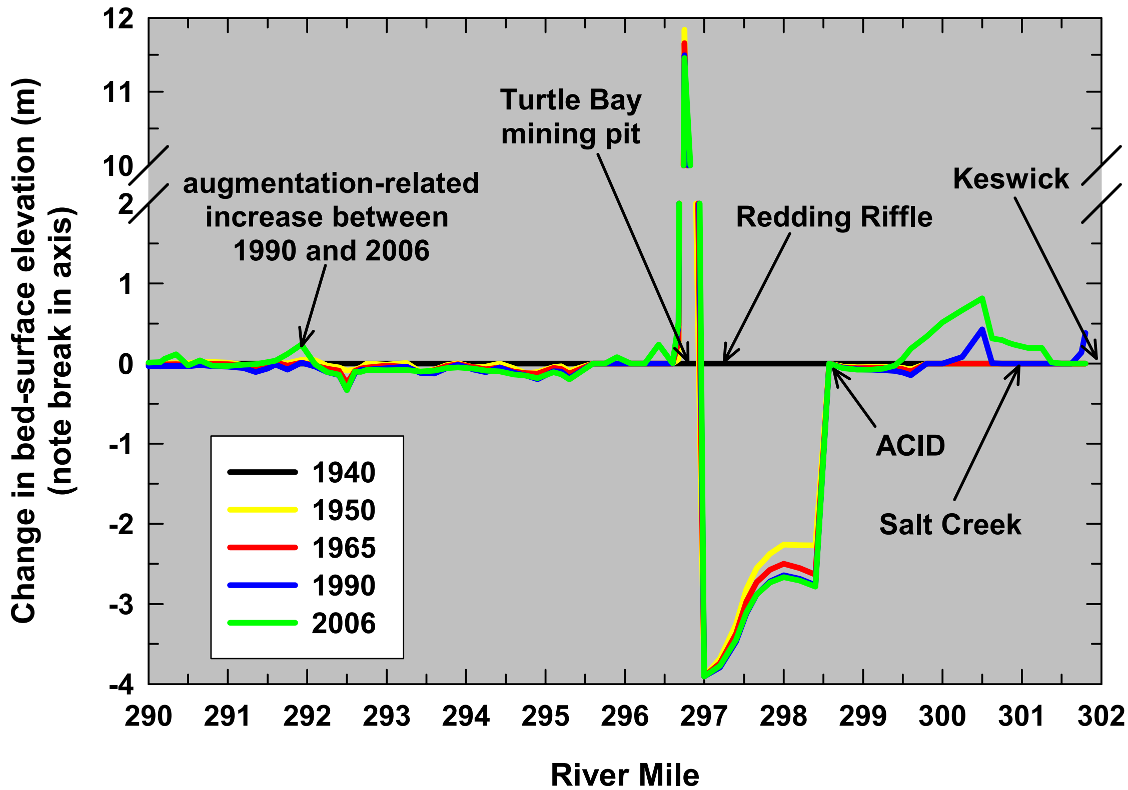


Figure 56. Predicted change in bed elevations (relative to initial conditions) at selected points in time for the upper river, based on TUGS model simulations. The initial depth of the mining pit at Turtle Bay was an unknown boundary condition that had to be assumed. Errors in the assumption would affect the magnitude but not the pattern of changes in the immediate vicinity of the pit. Simulations show an upstream-propagating wave of incision that decreases bed elevations upstream. The actual depth of incision may be limited by the bedrock depth, which, like the depth of the pit, is unknown. The bed is predicted to increase in elevation above RM 299, due to grade control at ACID dam and gravel augmentation at Salt Creek and Keswick Dam. Decreases in bed elevation occur below Turtle Bay, due to the system-wide shutdown in sediment supply. The increase in elevation near RM 290 is due to the simulated effects of gravel augmentation at Tobiasson and Shea Levee.

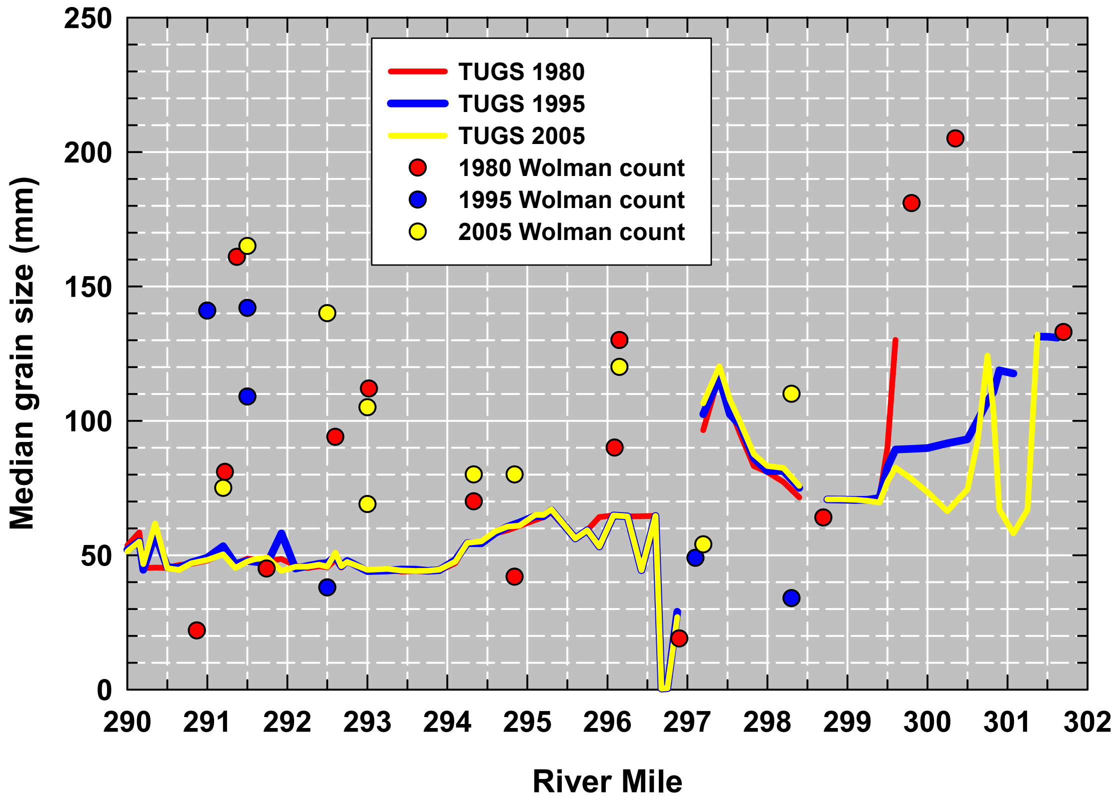


Figure 57. Median grain size versus river mile showing TUGS model predictions (lines) and measurements from Wolman counts (points) for 1980, 1995, and 2005. Agreement between predicted and measured values is about as good as can be expected, given that TUGS generates cross-sectional averages, rather than point measurements of D_{50}, and given the uncertainties in initial conditions for the model.

APPENDICES

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APPENDIX A

SUPPLEMENTAL FIGURES

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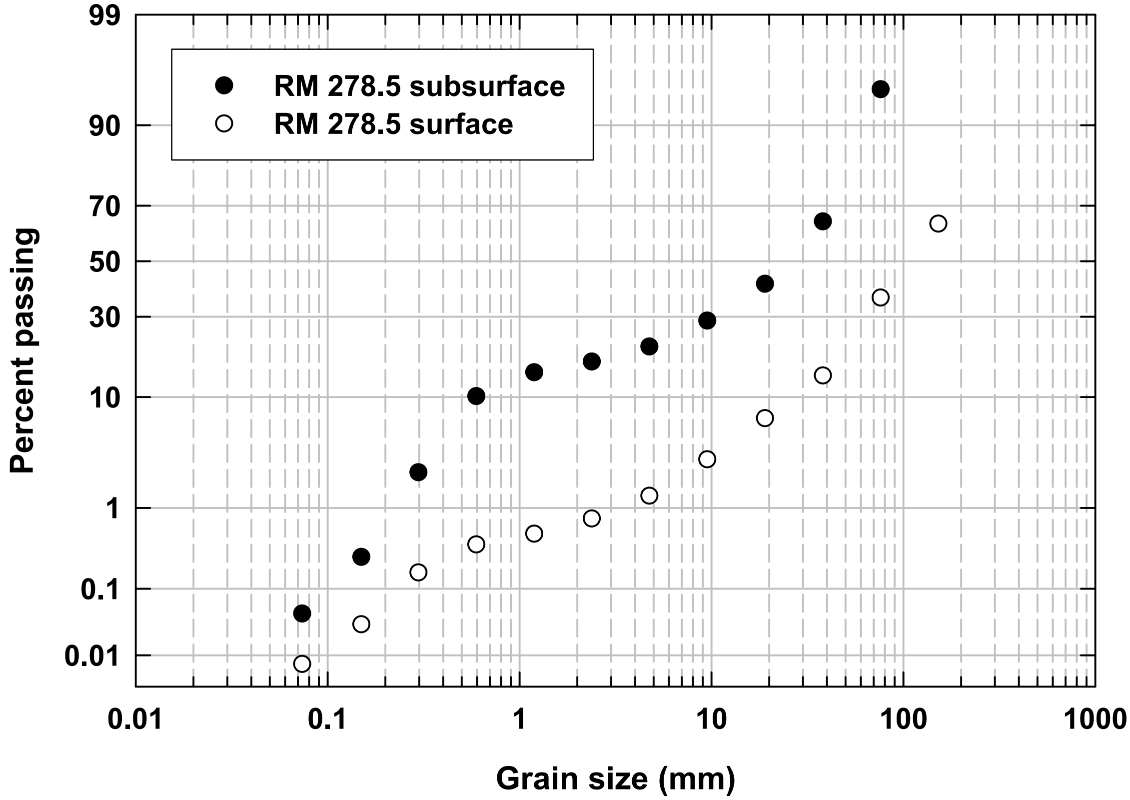
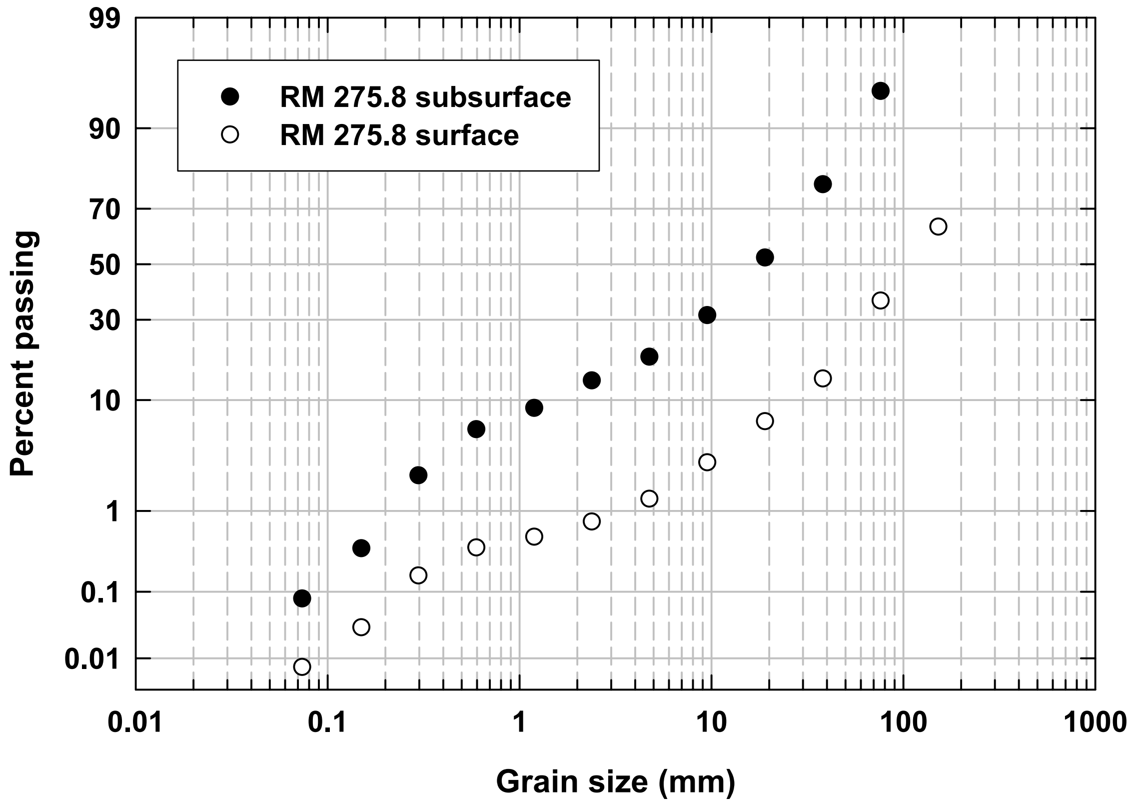
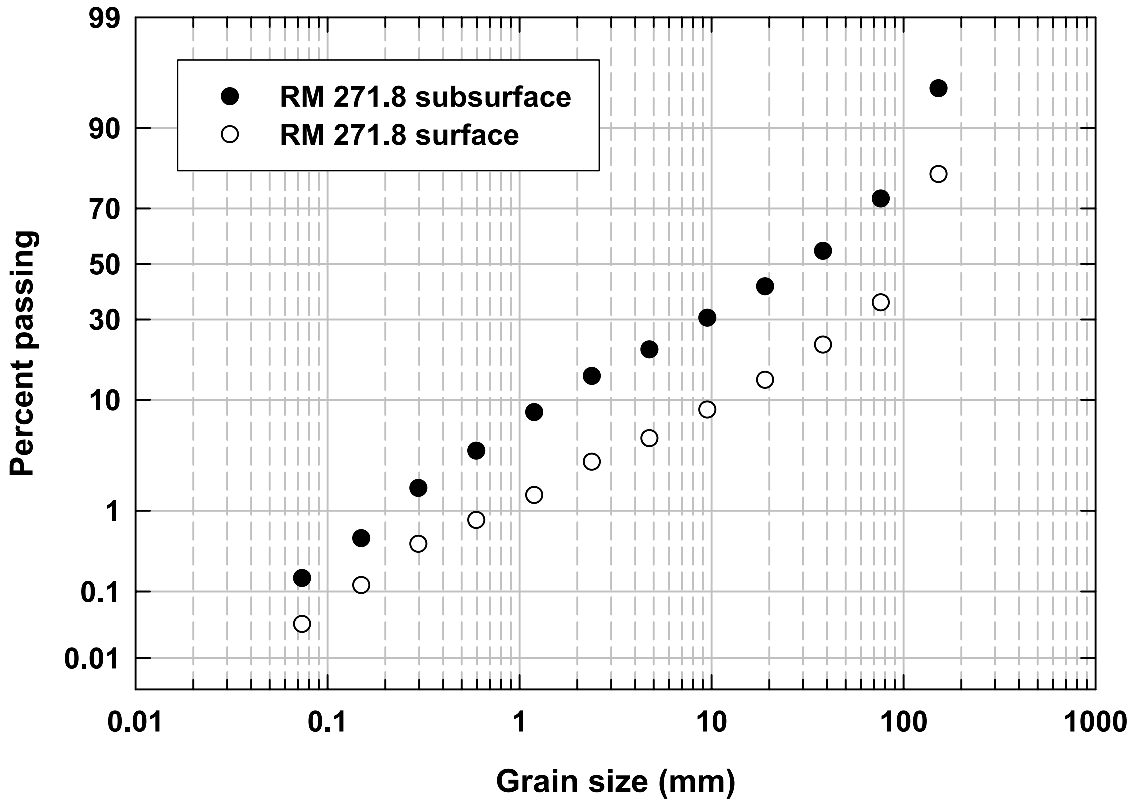


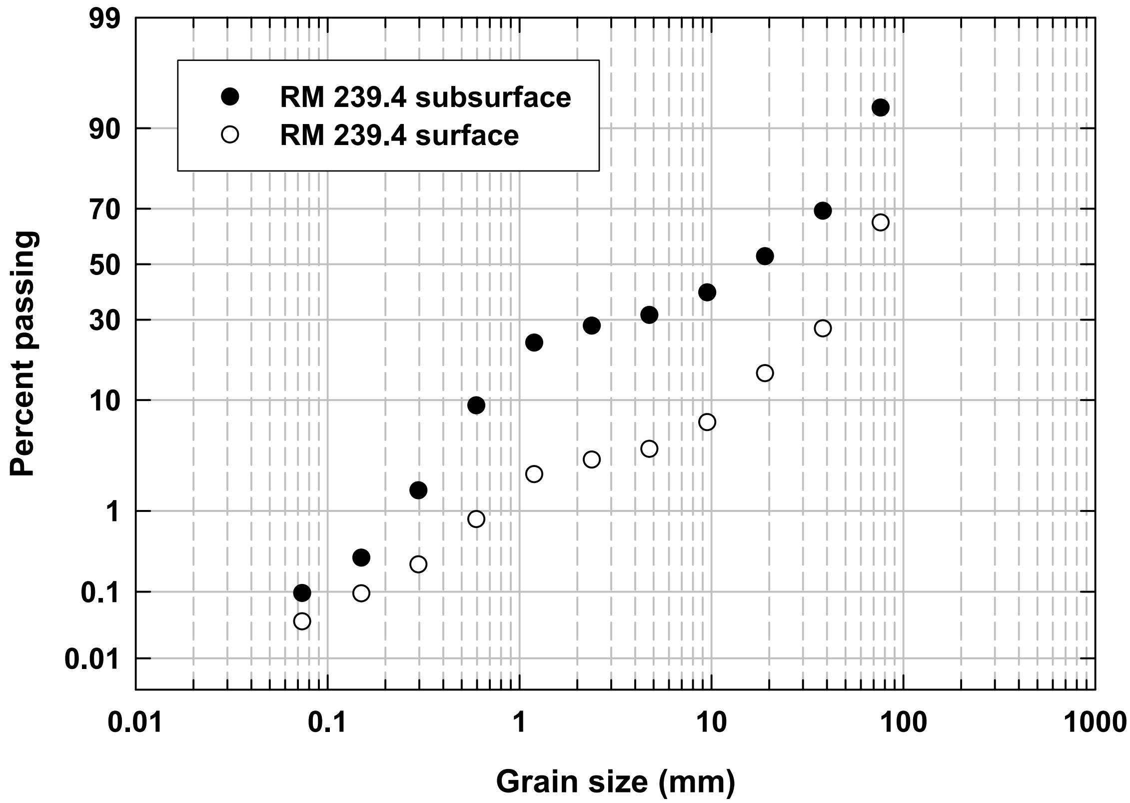
Appendix Figure BS1. Grain-size distribution from bulk sampling at RM 278.5 in 2005. Y axis is a probability scale.



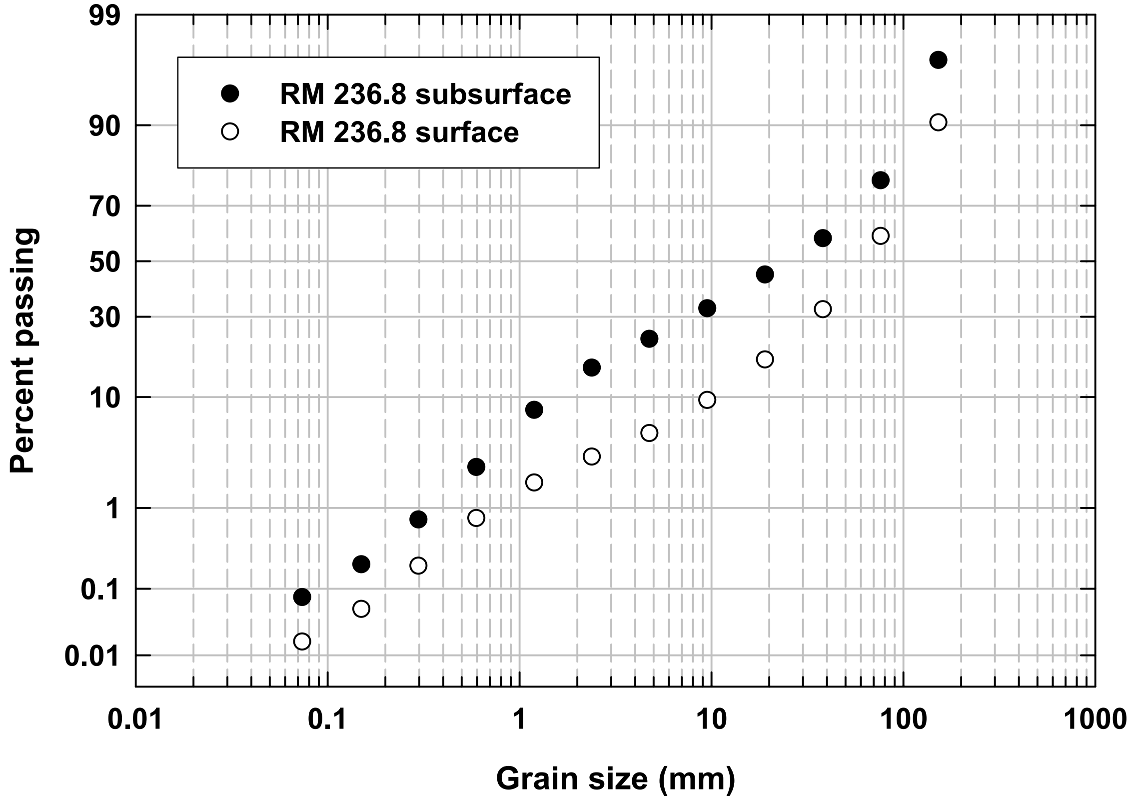
Appendix Figure BS2. Grain-size distribution from bulk sampling at RM 275.8 in 2005. Y axis is a probability scale.



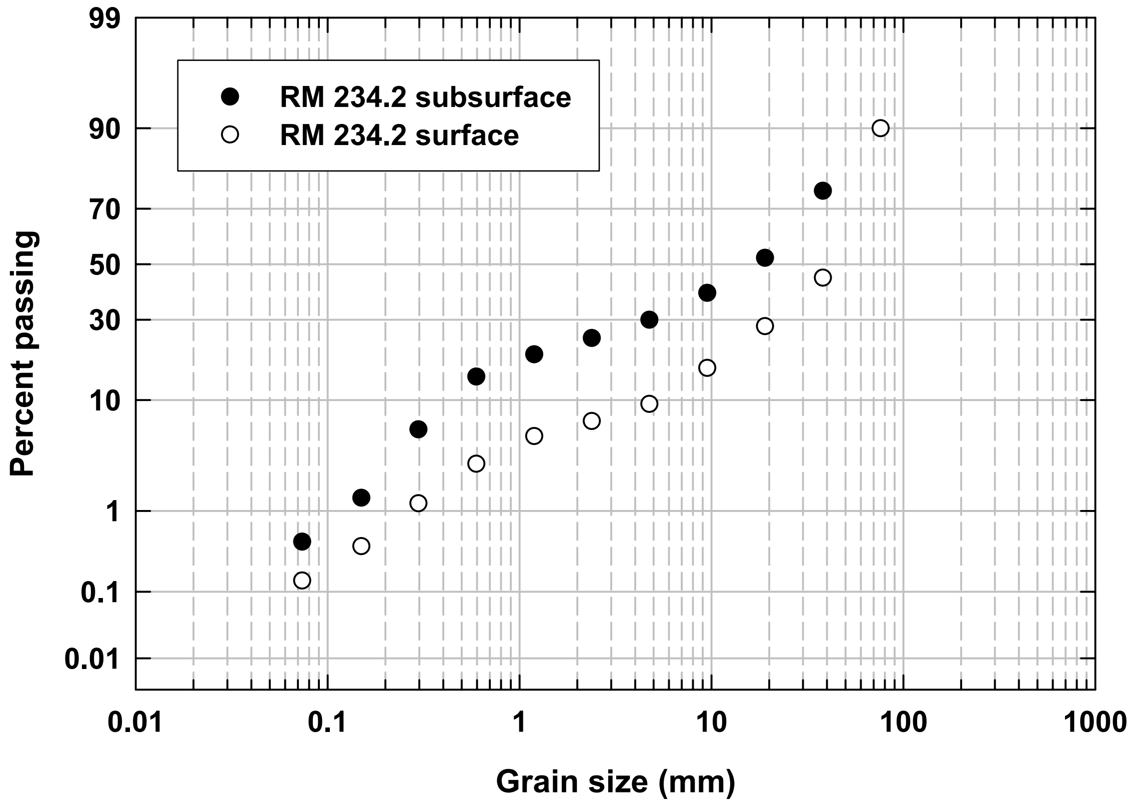
Appendix Figure BS3. Grain-size distribution from bulk sampling at RM 271.8 in 2005. Y axis is a probability scale.



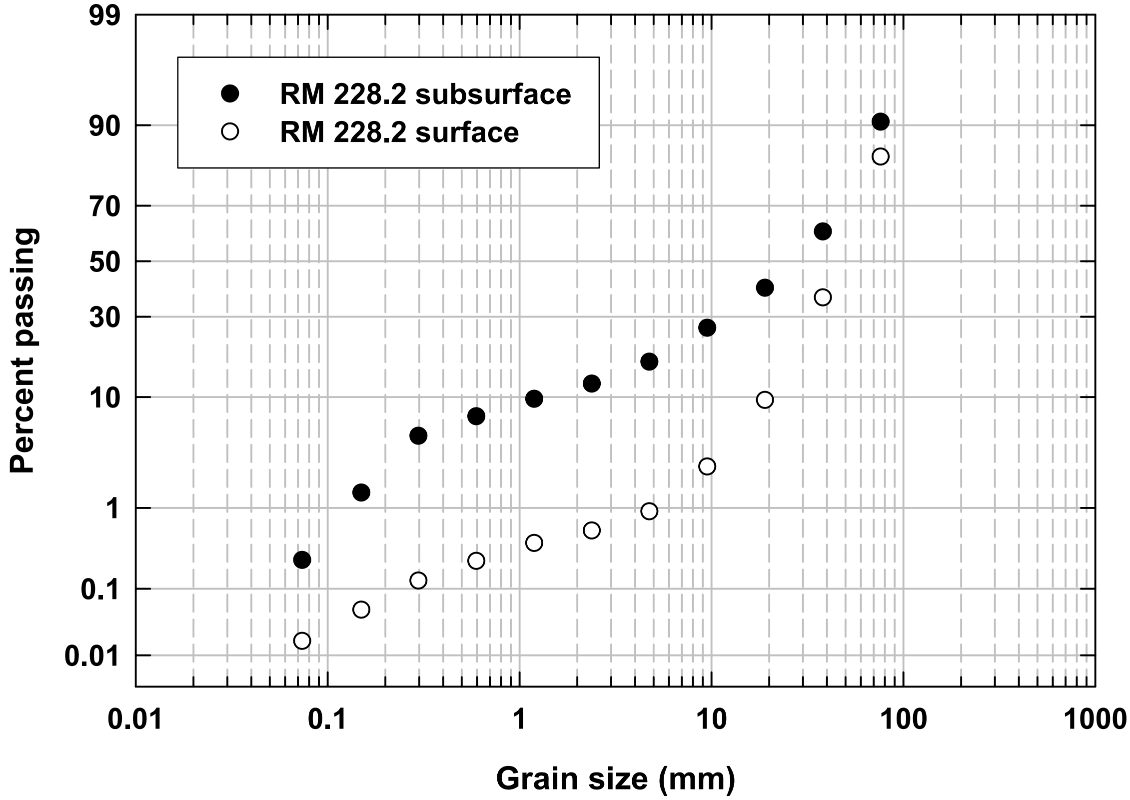
Appendix Figure BS4. Grain-size distribution from bulk sampling at RM 239.4 in 2005. Y axis is a probability scale.



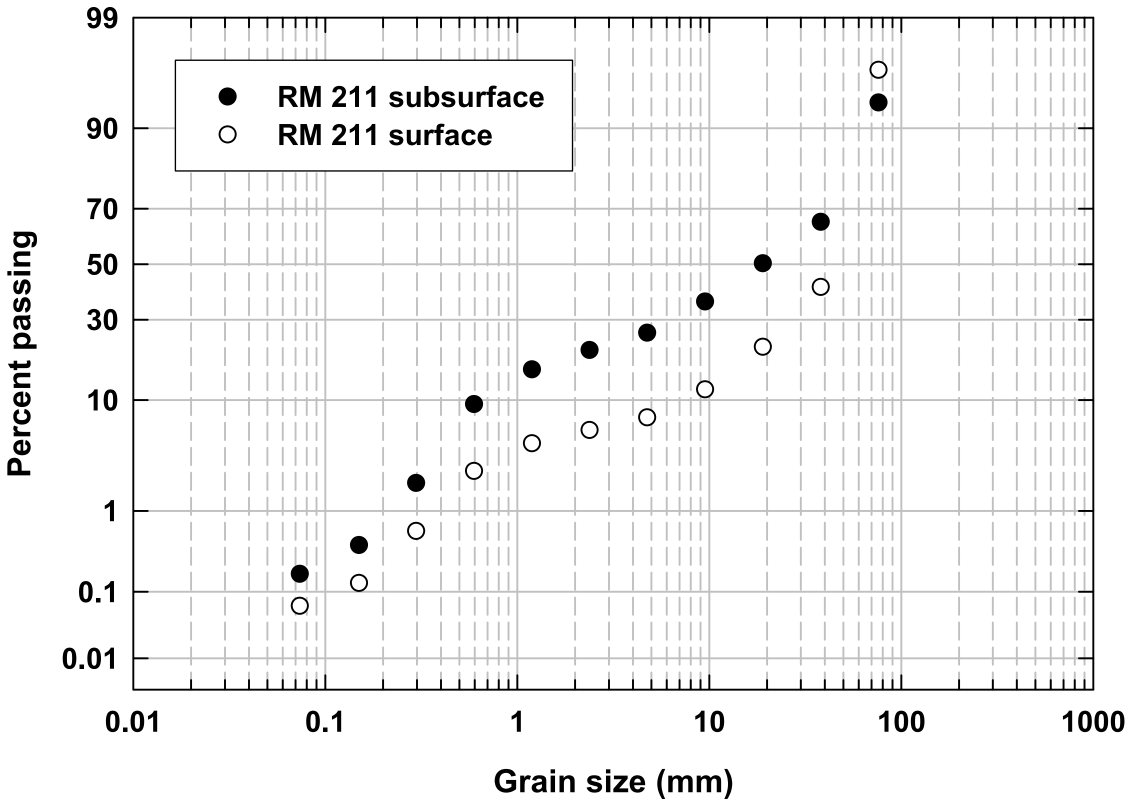
Appendix Figure BS5. Grain-size distribution from bulk sampling at RM 236.8 in 2005. Y axis is a probability scale.



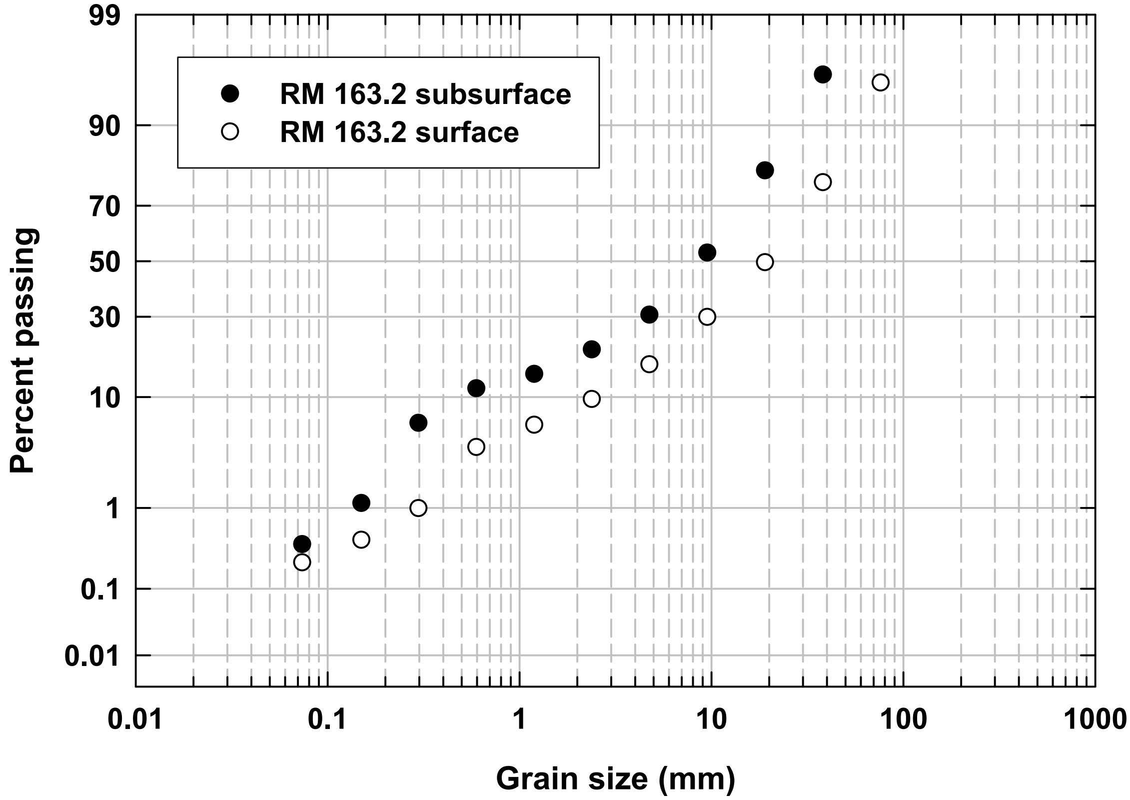
Appendix Figure BS6. Grain-size distribution from bulk sampling at RM 234.2 in 2005. Y axis is a probability scale.



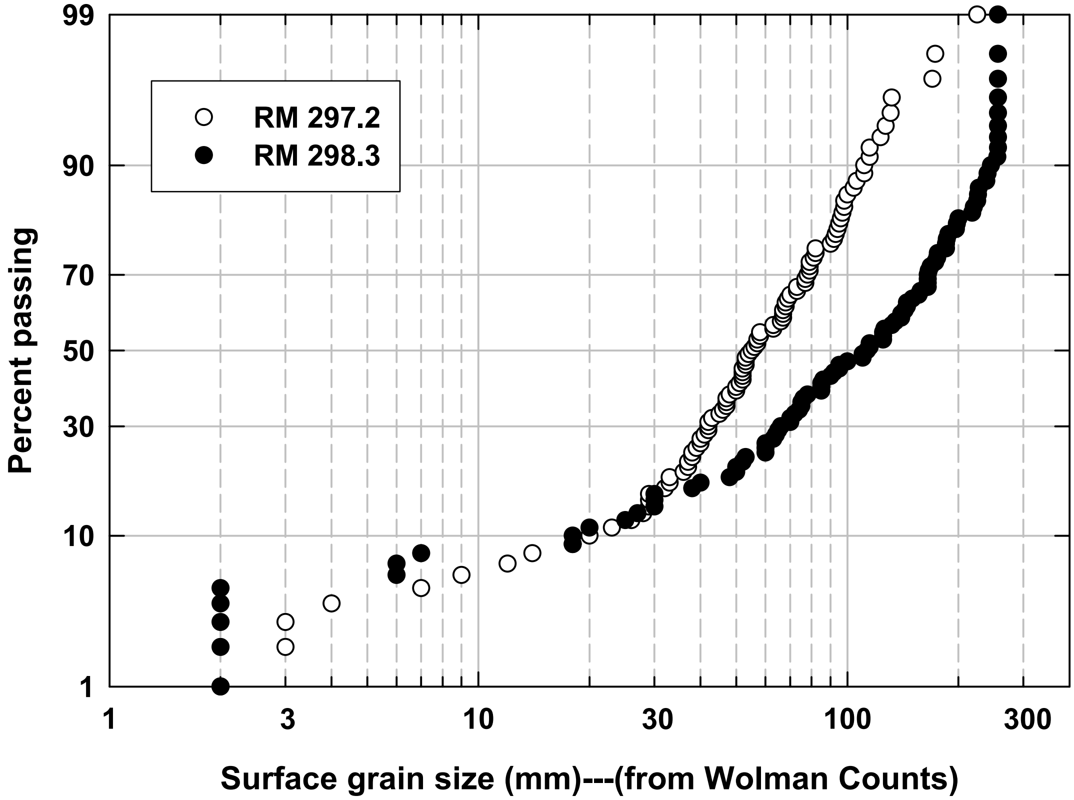
Appendix Figure BS7. Grain-size distribution from bulk sampling at RM 228.2 in 2005. Y axis is a probability scale.



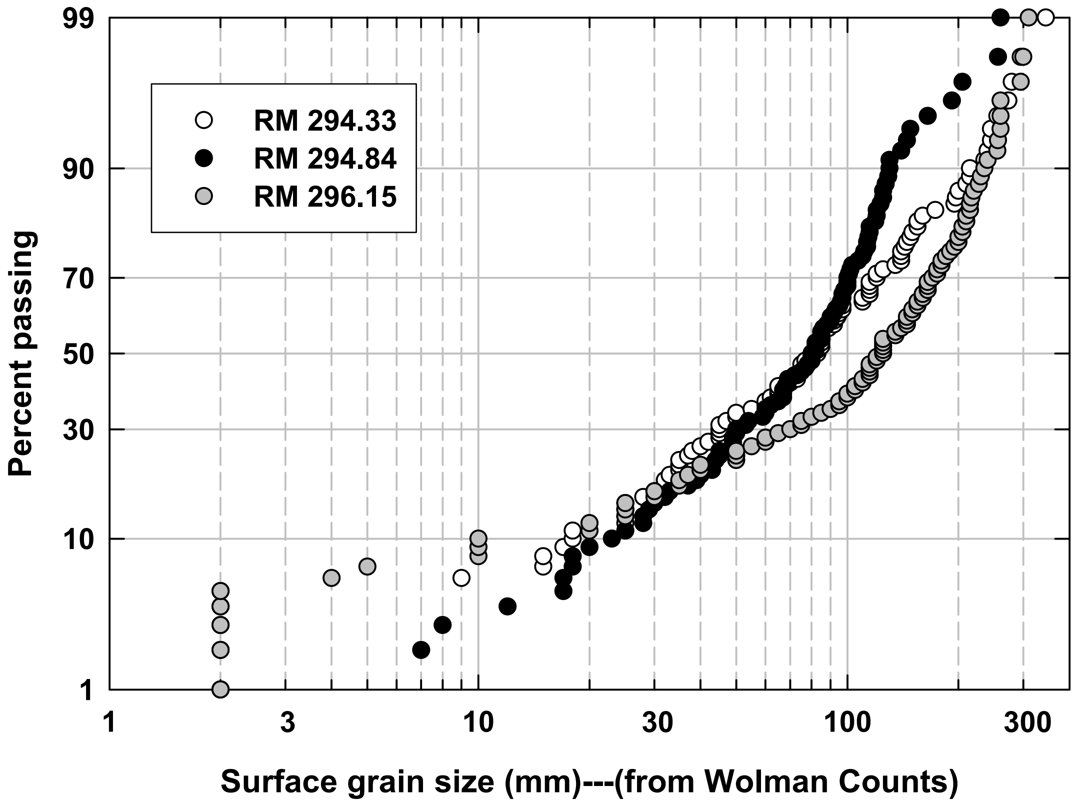
Appendix Figure BS8. Grain-size distribution from bulk sampling at RM 211 in 2005. Y axis is a probability scale.



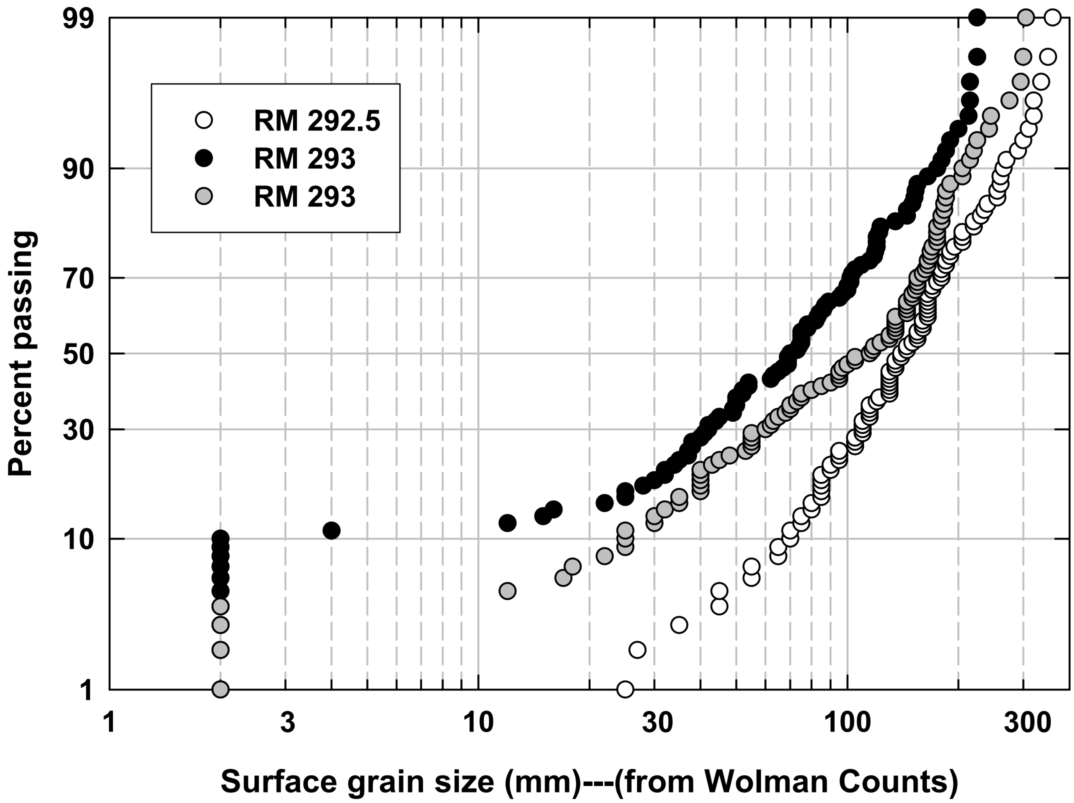
Appendix Figure BS9. Grain-size distribution from bulk sampling at RM 163.2 in 2005. Y axis is a probability scale.



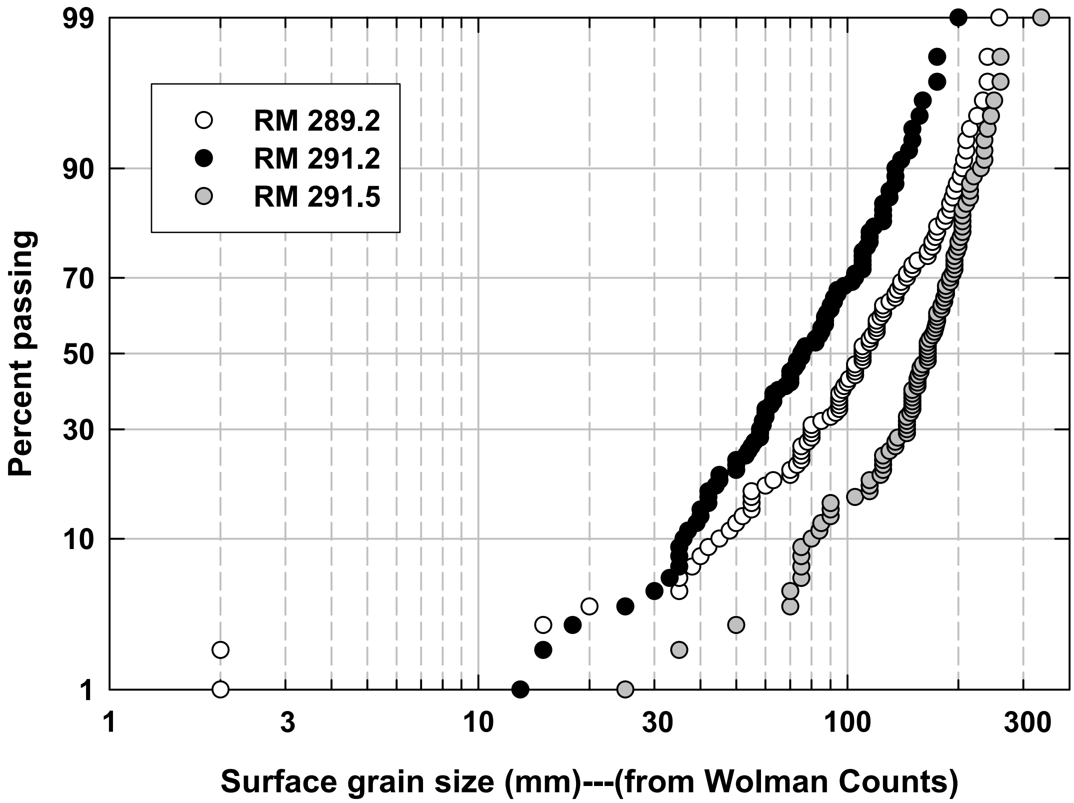
Appendix Figure WC1. Grain-size distributions of the surface inferred from Wolman Counts at 2 locations on the Sacramento River in 2005. The Y axis shows a probability scale.



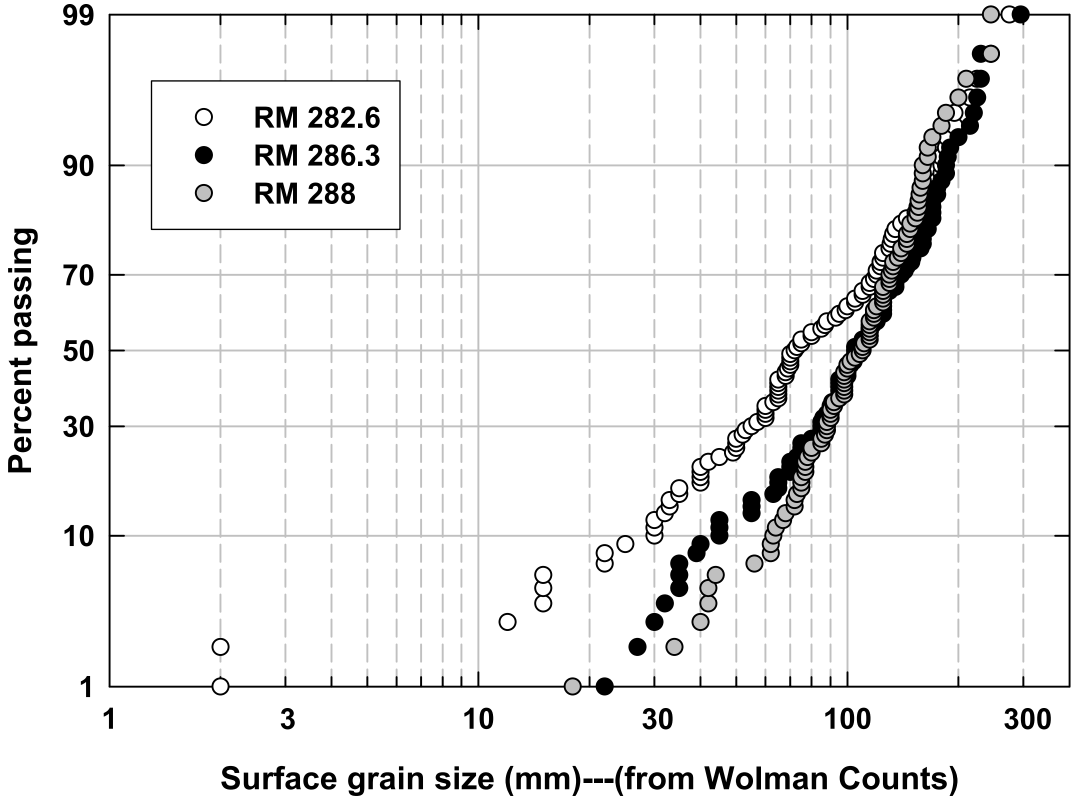
Appendix Figure WC2. Grain-size distributions of the surface inferred from Wolman Counts at 3 locations on the Sacramento River in 2005. The Y axis shows a probability scale.



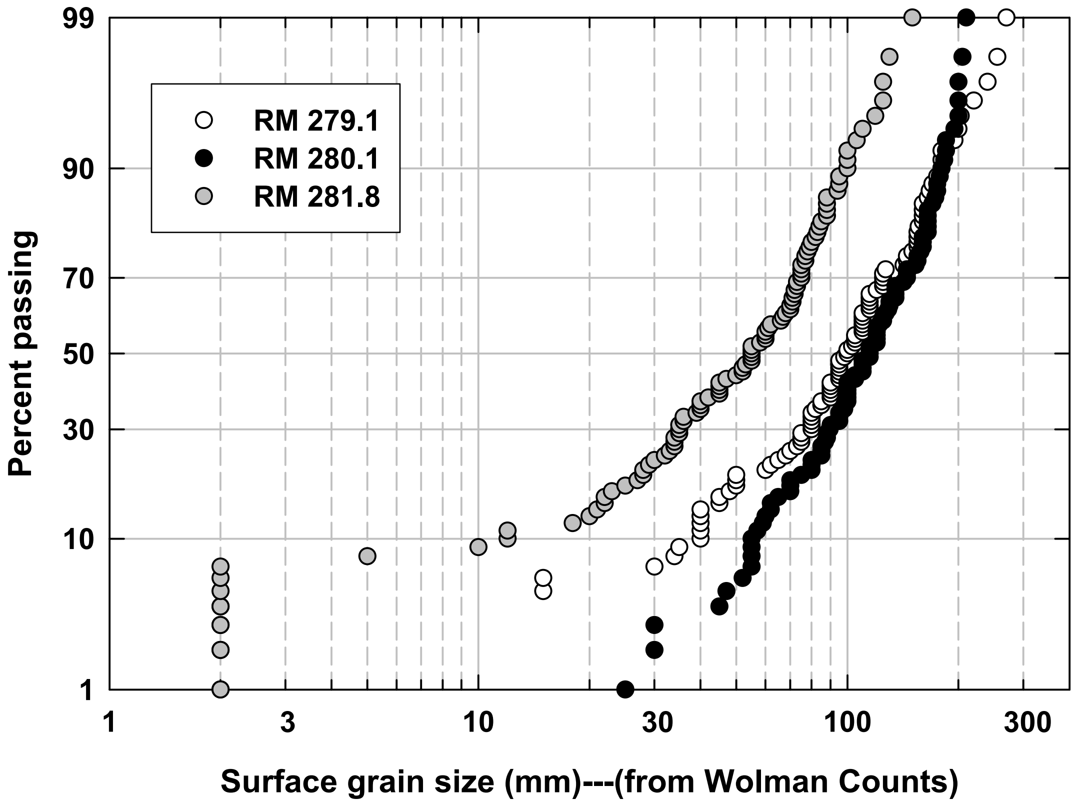
Appendix Figure WC3. Grain-size distributions of the surface inferred from Wolman Counts at 3 locations on the Sacramento River in 2005. The Y axis shows a probability scale.



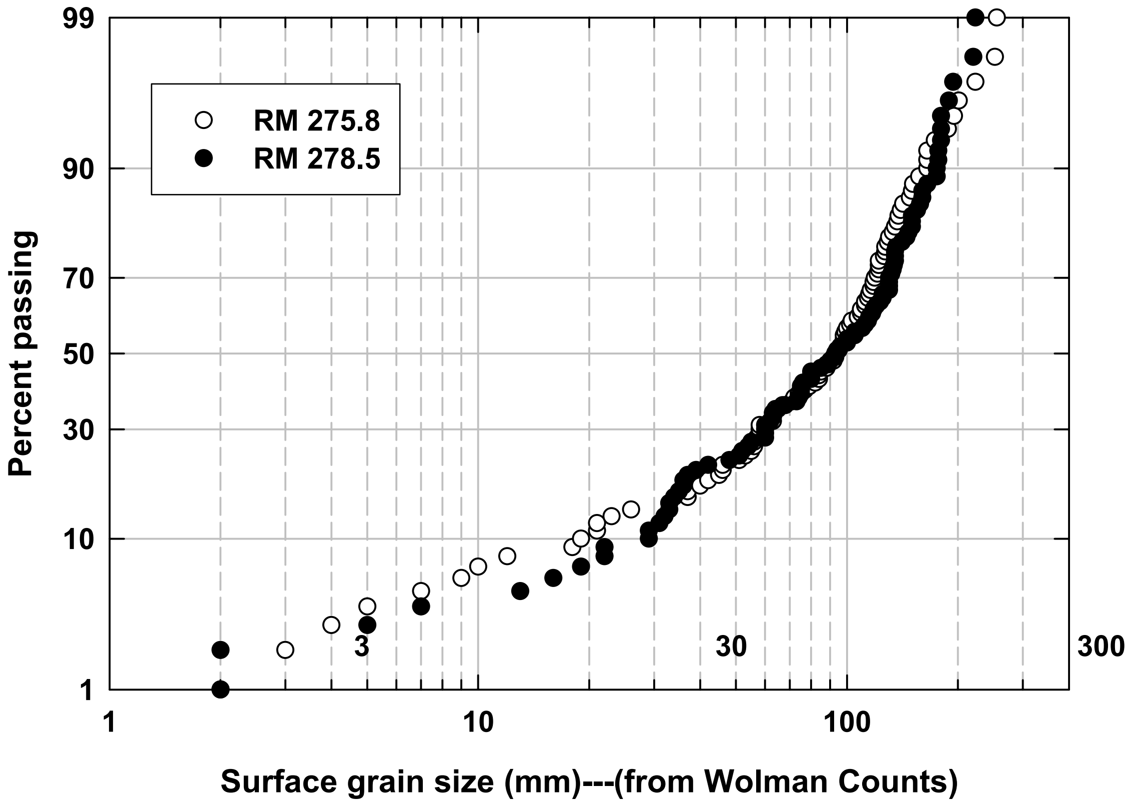
Appendix Figure WC4. Grain-size distributions of the surface inferred from Wolman Counts at 3 locations on the Sacramento River in 2005. The Y axis shows a probability scale.



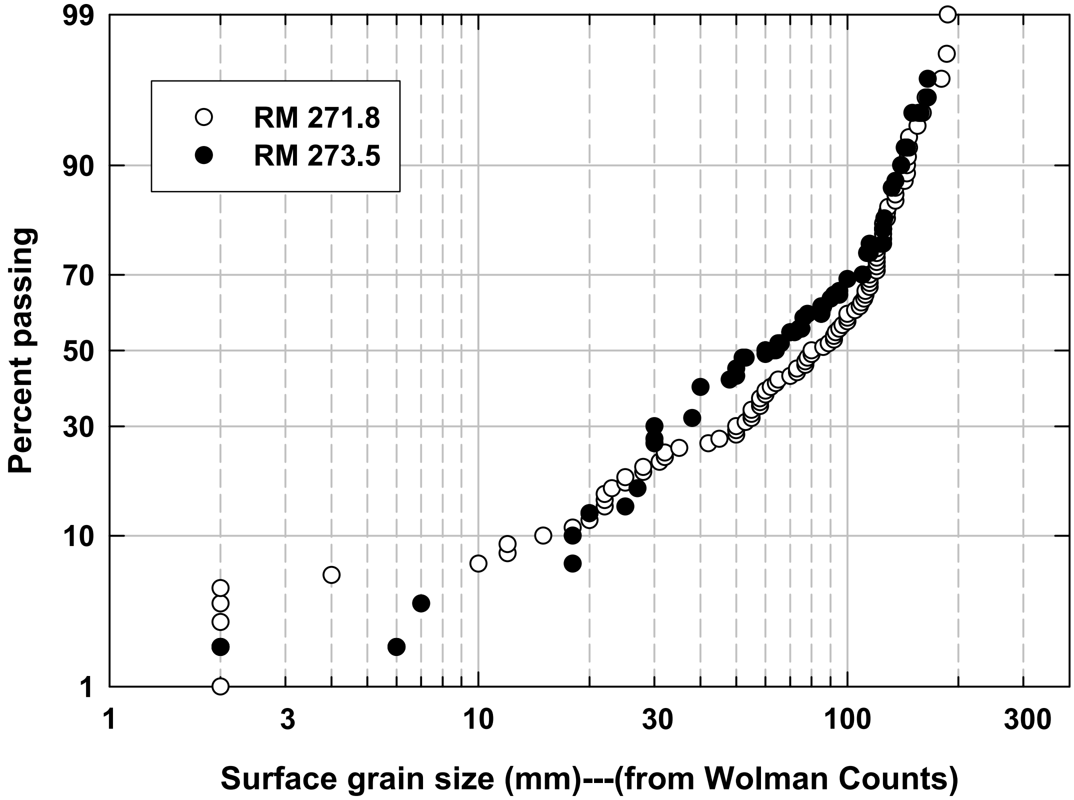
Appendix Figure WC5. Grain-size distributions of the surface inferred from Wolman Counts at 3 locations on the Sacramento River in 2005. The Y axis shows a probability scale.



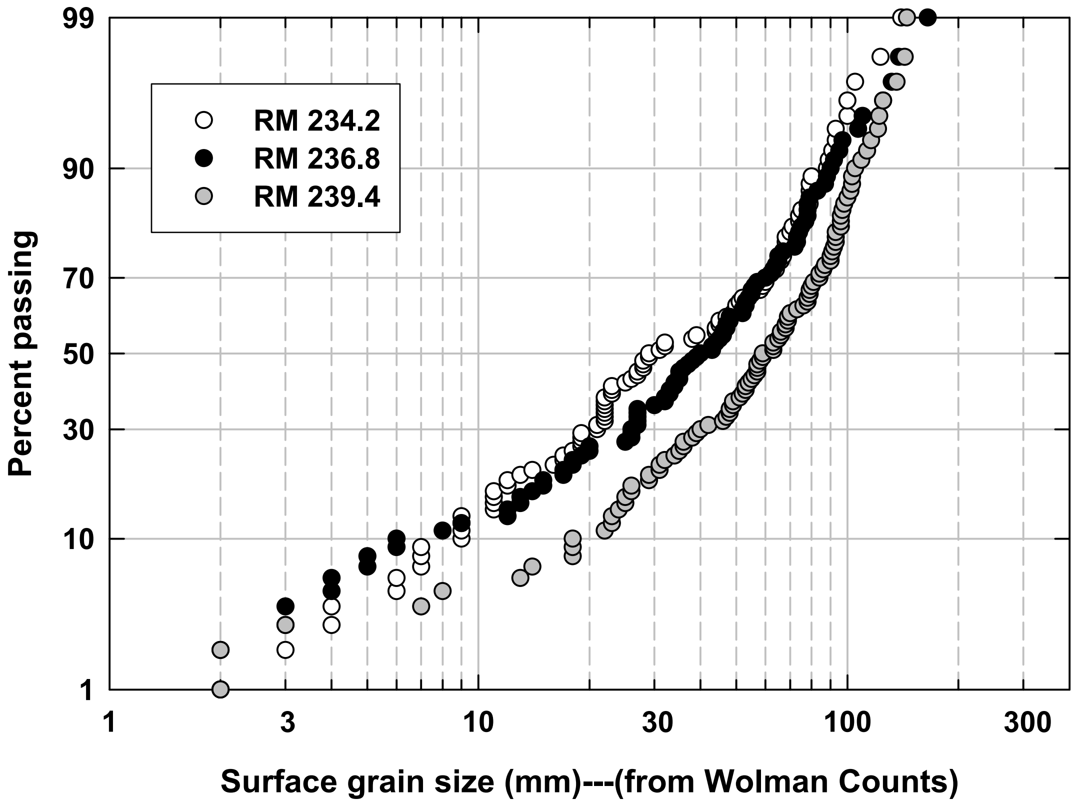
Appendix Figure WC6. Grain-size distributions of the surface inferred from Wolman Counts at 3 locations on the Sacramento River. The Y axis shows a probability scale.



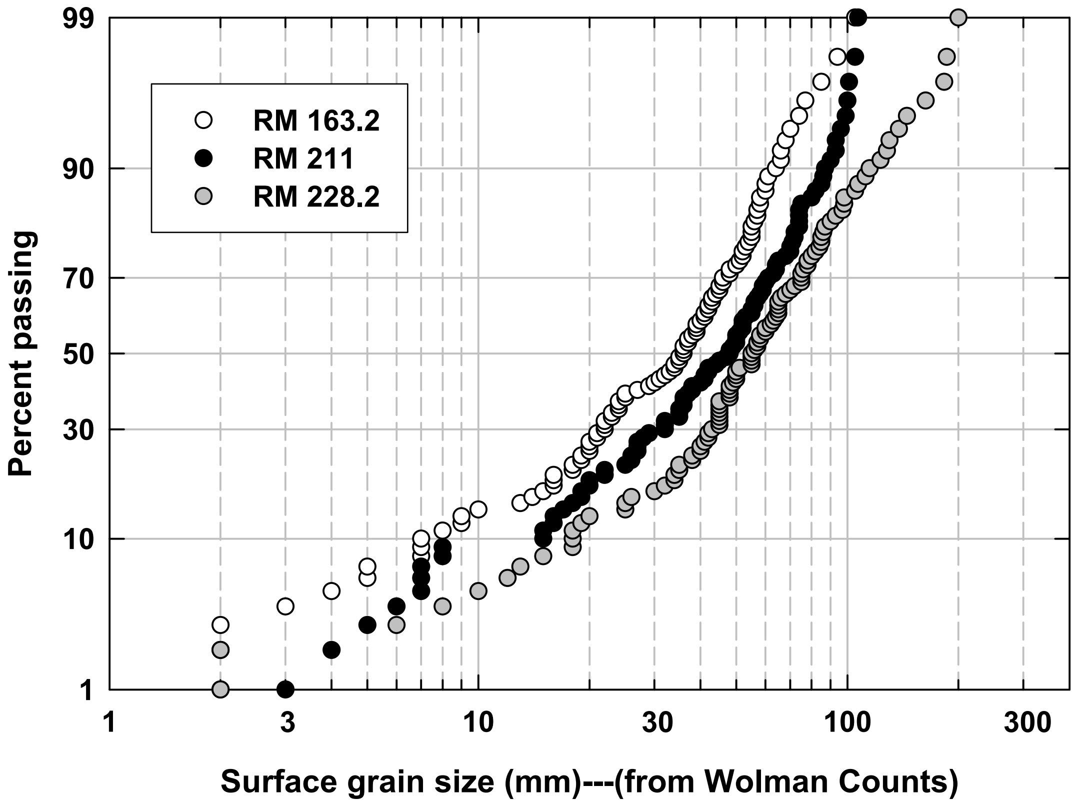
Appendix Figure WC7. Grain-size distributions of the surface inferred from Wolman Counts at 3 locations on the Sacramento River in 2005. The Y axis shows a probability scale.



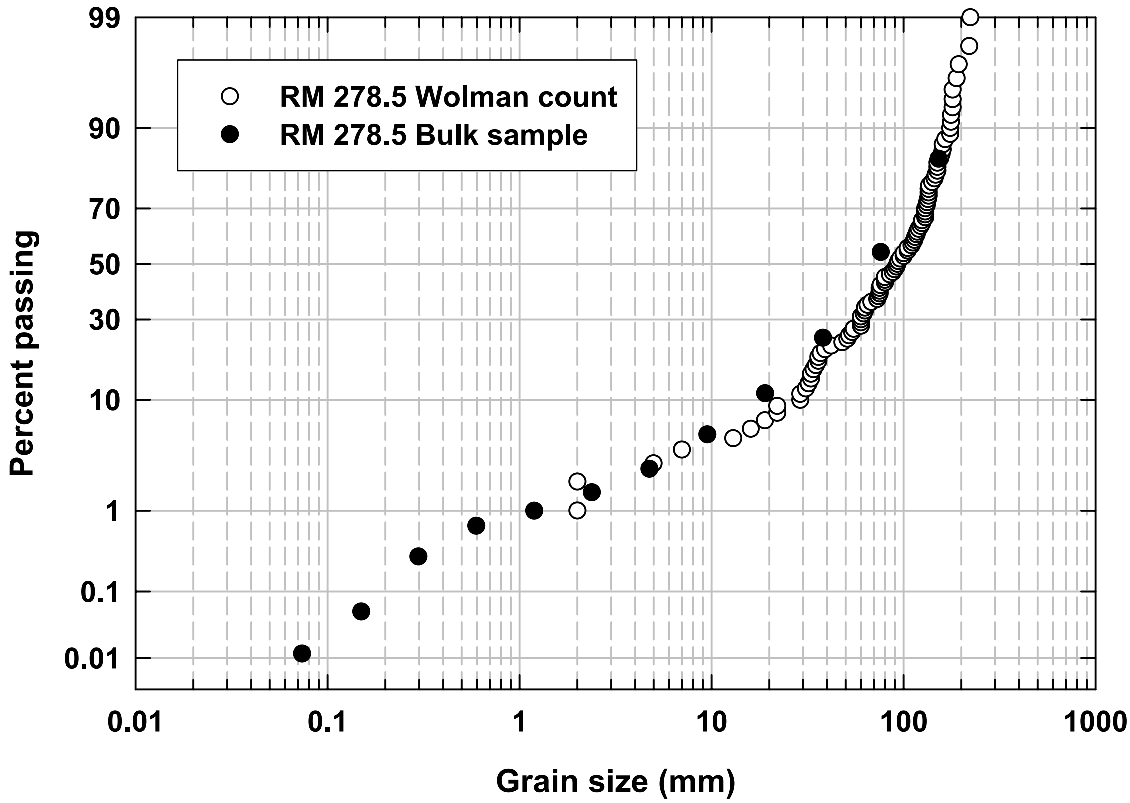
Appendix Figure WC8. Grain-size distributions of the surface inferred from Wolman Counts at 3 locations on the Sacramento River in 2005. The Y axis shows a probability scale.



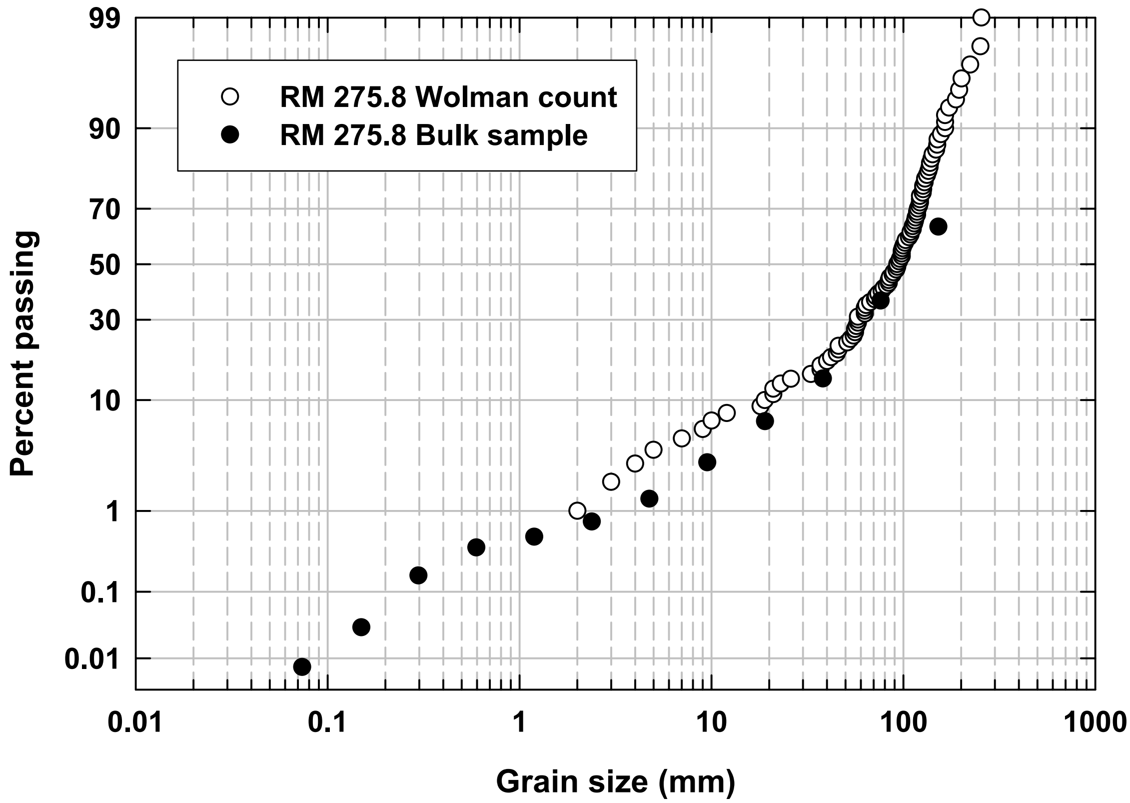
Appendix Figure WC9. Grain-size distributions of the surface inferred from Wolman Counts at 3 locations on the Sacramento River in 2005. The Y axis shows a probability scale.



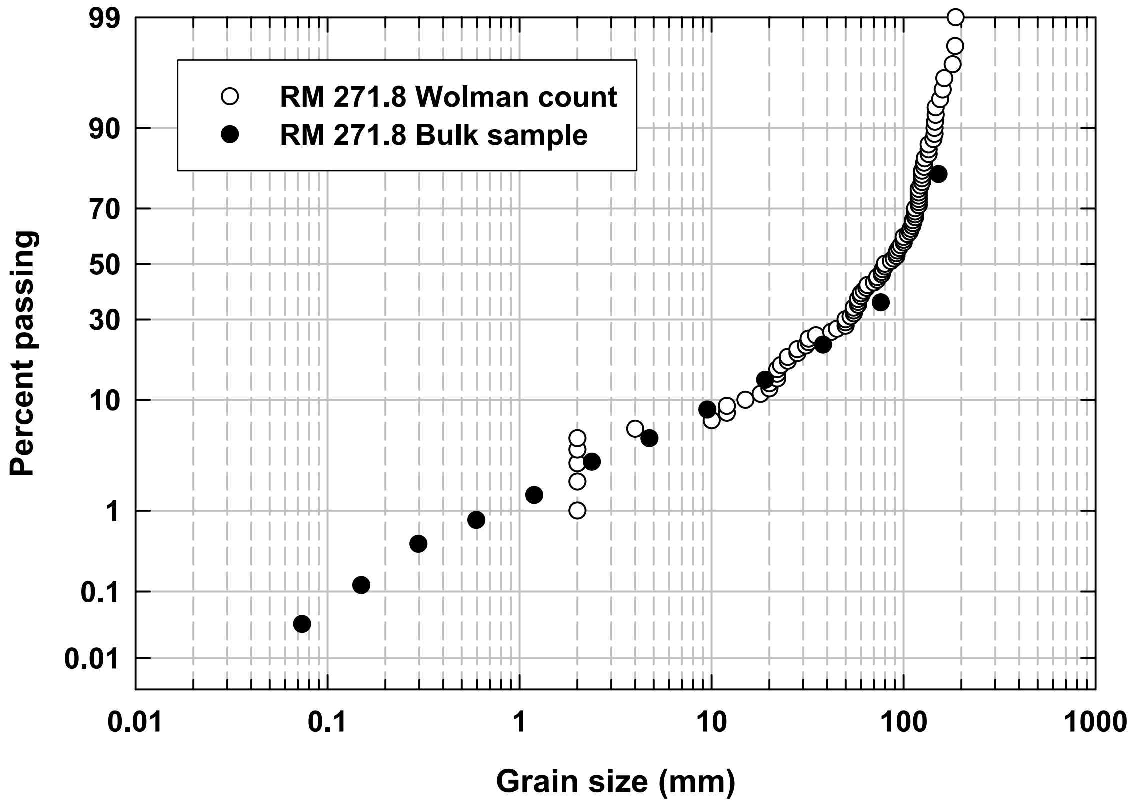
Appendix Figure WC10. Grain-size distributions of the surface inferred from Wolman Counts at 3 locations on the Sacramento River in 2005. The Y axis shows a probability scale.



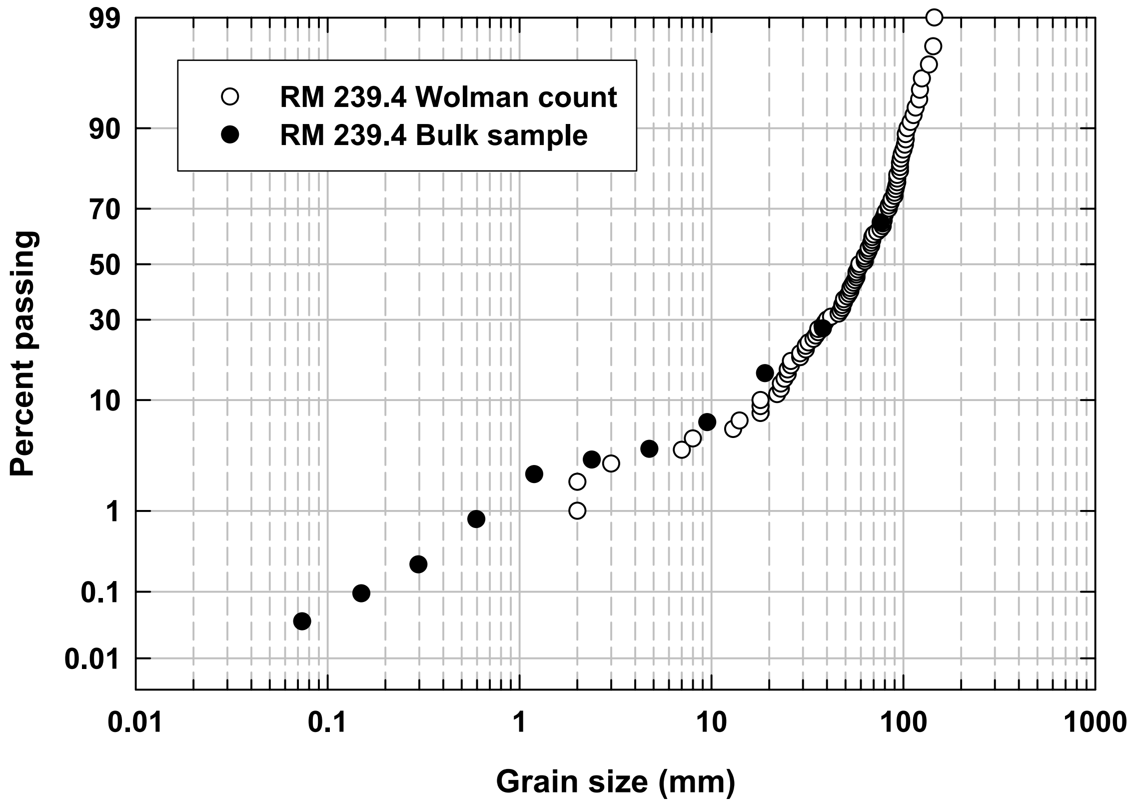
Appendix Figure COMP1. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.



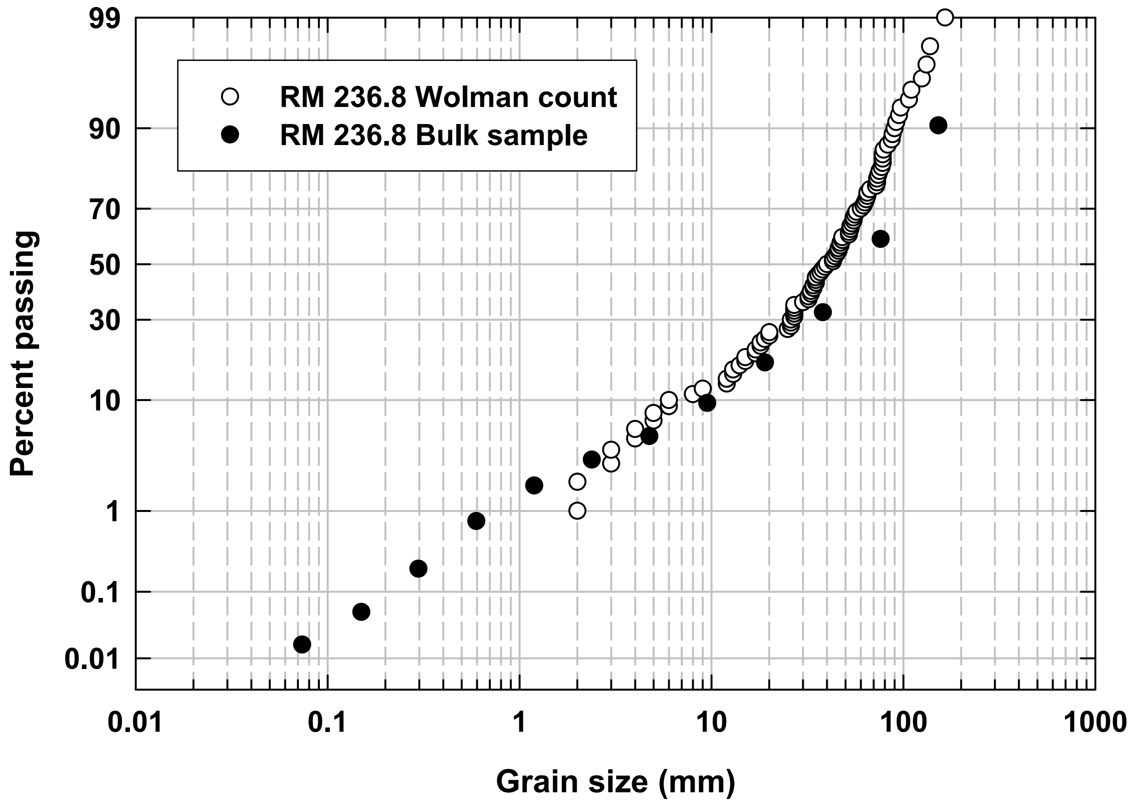
Appendix Figure COMP2. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.



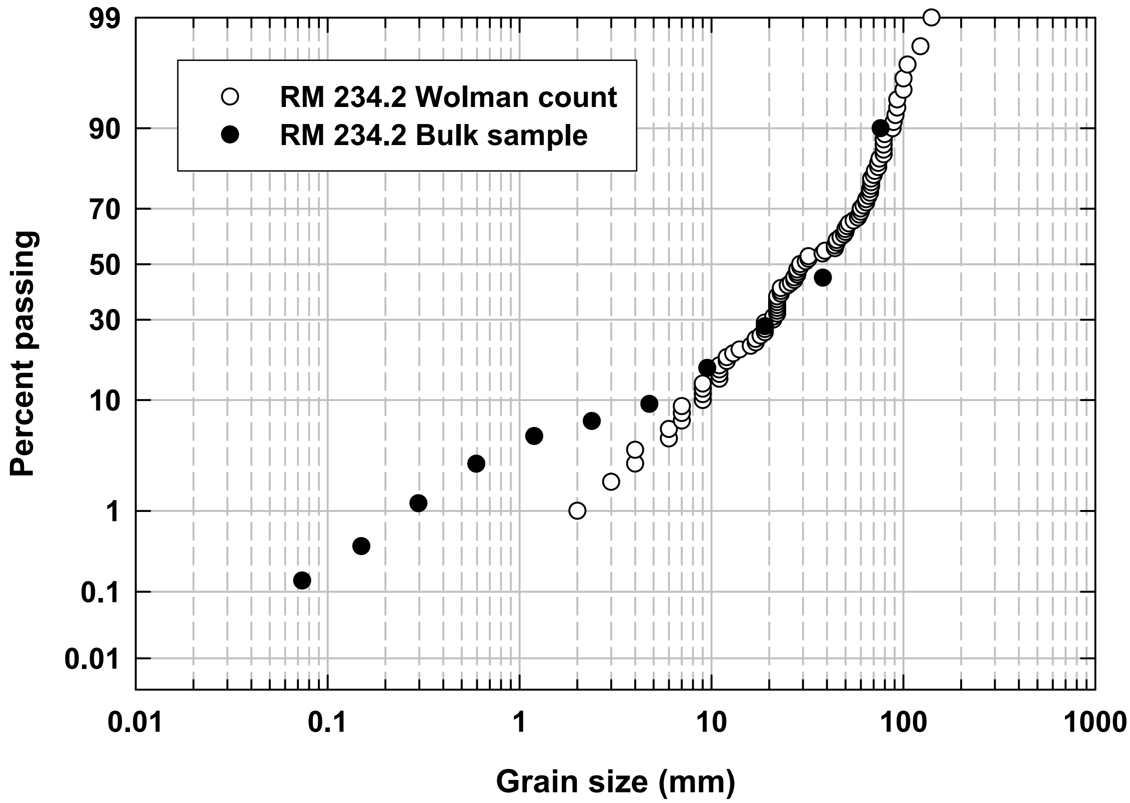
Appendix Figure COMP3. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.



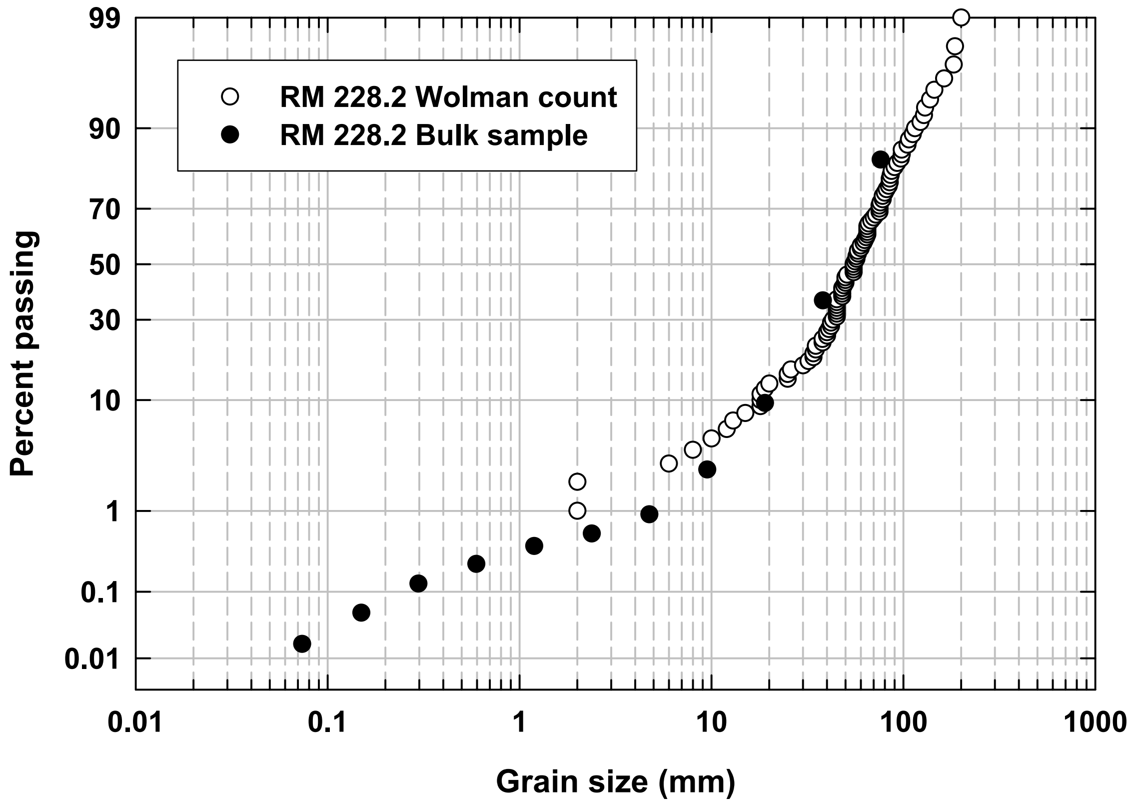
Appendix Figure COMP4. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.



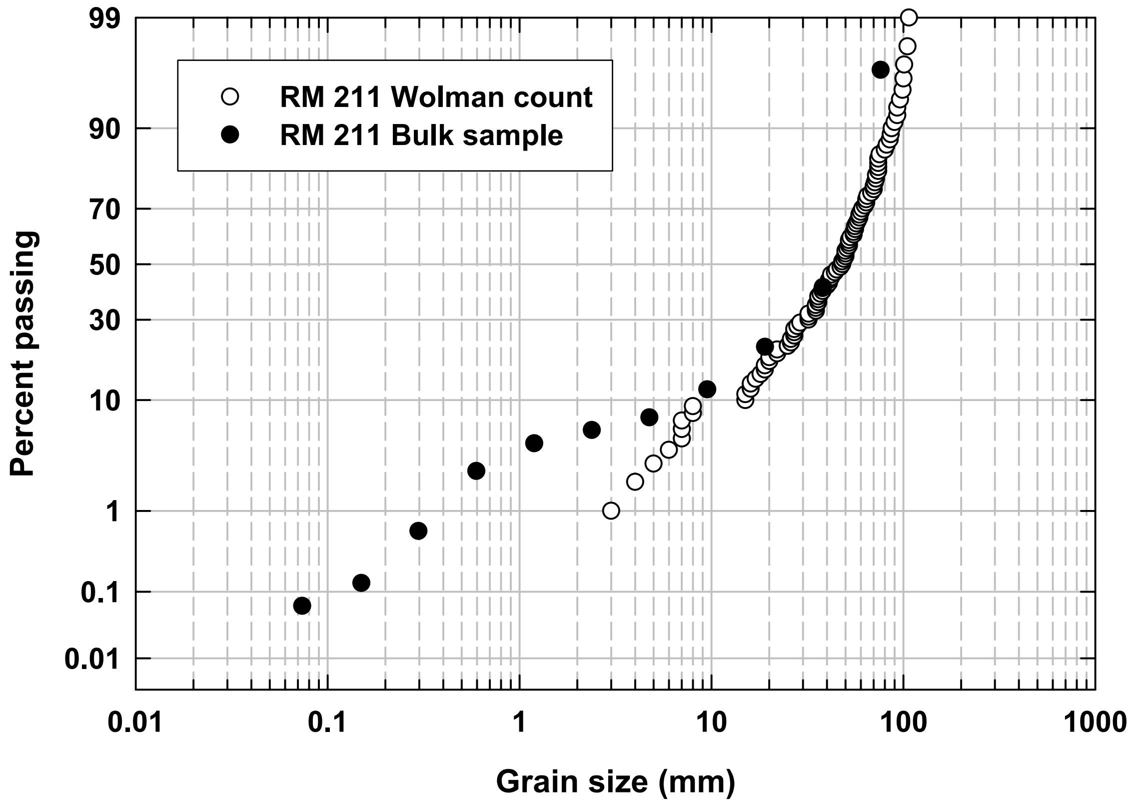
Appendix Figure COMP5. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.



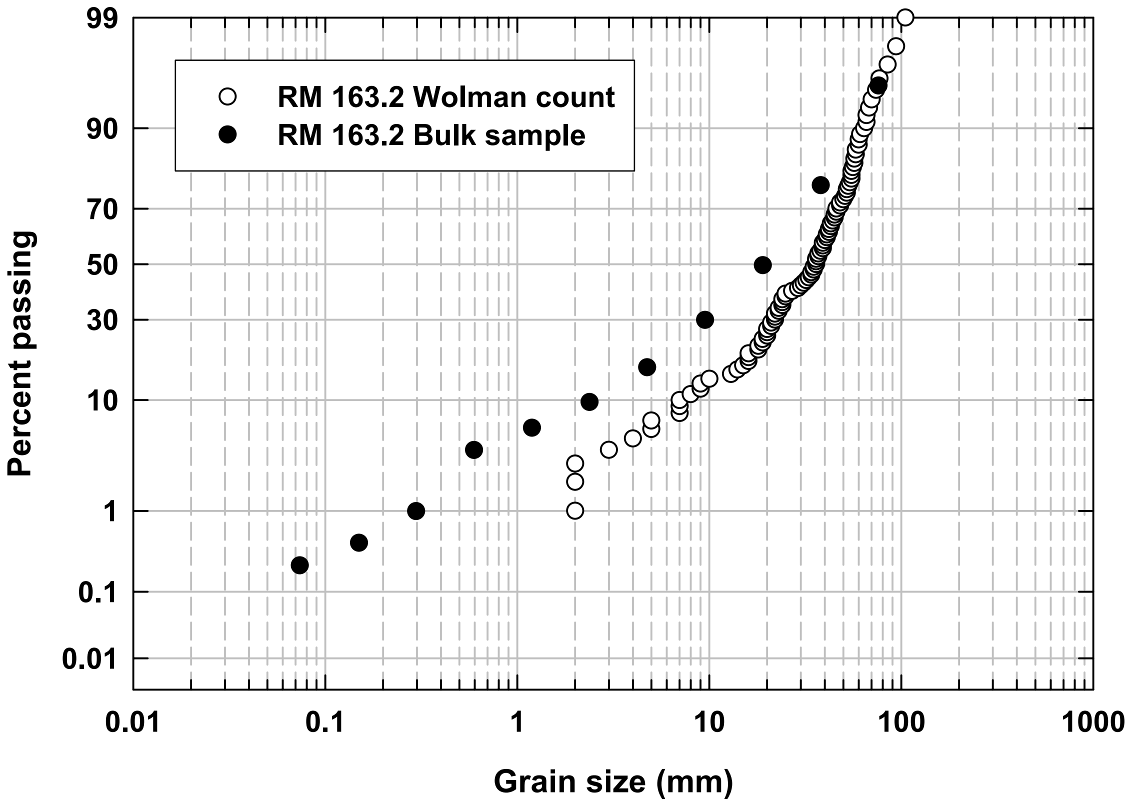
Appendix Figure COMP6. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.



Appendix Figure COMP7. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.



Appendix Figure COMP8. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.



Appendix Figure COMP9. Grain-size distributions of the surface inferred from a Wolman count (open symbols) and a bulk sample (closed symbols) for a site on the Sacramento River in 2005. The Y axis shows a probability scale.

APPENDIX B

SUPPLEMENTAL DATA (INCLUDED IN A SEPARATE MS EXCEL FILE)

Gravel Study Tech Memo Appendix B.xls

Sacramento Ecological Flows: Gravel Study Sampling Locations

Location name	RM	Types and number of data collected							
		bulk samples	Wolman counts	perm sites with 3 depths each	freeze cores (includes 1 set perm measure-ments)	scour chains (at head of riffle, at the corners of a 5x5 m grid)	In-situ painting (5x5 ft boxes, spaced 20 m apart starting at head of riffle)	Access point	Notes
SW-9	163.2	√	√	√	0			Princeton levee road	gravel is relatively fine and loose with high permeabilities
SW-5	211	√	√	√	0			Woodson Bridge	
SW-1	228.2	√	√	√	0	√	√	Mill Creek	
SW-4	234.2	√	√	√	0			Lower Red Bluff	
SW-3	236.8	√	√	√	0	√	√	Lower Red Bluff	
SW-2	239.4	√	√	√	√	√	√	Lower Red Bluff	ran out of daylight and batteries on one of the perm sites
SW-11	246.2					√		Red Bluff Riffle	
SW-6	271.8	√	√	√	√	failed attempt (material was too coarse)	√	Balls Ferry	hit refusal at 12 inches on one of the perm sites
SW-10	273		√			√	√	Balls Ferry	just downstream of cottonwood
SW-8	275.8	√	√	√	0			Balls Ferry	very coarse, but perms seem low at depth
SW-7	278.5	√	√	√	0			Balls Ferry	very coarse, but perms seem low at depth
SWW-17	279.1		√					Anderson	analog to SBG-16
SWW-16	280.1		√					Anderson	analog to SBG-15
SWW-15	281.8		√					Anderson	analog to SR-84 and SBG-12
SWW-14	282.6		√					Anderson	analog to SR-80 and SBG-14
SWW-13	286.3		√					Anderson	analog to SR-35, 36 and SBG-1
SWW-12	288		√					Redding	analog to SR-30
SWW-11	289.2		√					Redding	analog to SR-24
SWW-10	291.2		√					Redding	analog to SR-19
SWW-9	291.5		√					Redding	analog to SBG-5
SWW-8	292.5		√					Redding	analog to SBG-9
SWW-7	293		√					Redding	analog to SR-13
SWW-6	293.02		√					Redding	analog to SR-13
SWW-5	294.33		√					Redding	analog to SR-12
SWW-4	294.84		√					Redding	analog to SR-11 a and b
SWW-3	296.15		√					Redding	analog to SR-93
SWW-2	297.2		√					Redding	analog to SBG-10
SWW-1	298.3		√					Redding	analog to SBG-8
Totals		**0**	**0**	**0**	**0**	**0**	**0**		

Source file: 265 2300 Field Sampling Summary

Mean permeability estimates by location and depth

(geometric means, no temperature corrections)

				permeability (cm/hr) at depth in inches with lower and upper confidence limits										Number of samples by depth			
rm	location	year	raking	6 in	-	+	12 in	-	+	18 in	-	+	14 in	6 in	12 in	18 in	14 in
278.5	SW-7	2005	before	1946	424.293	8921.896	227	34.440	1495.567	32	8.721	118.684		5	5	3	0
278.5	SW-7	2005	after	5844	1274.352	26796.676	273	41.475	1801.073					2	2	0	0
275.8	SW-8	2005	before	36	7.772	163.417	881	133.764	5808.733	51	13.902	189.186		2	2	2	0
271.8	SW-6	2005	before	68	14.758	310.333	126	19.085	828.781	310	84.033	1143.595	350	2	2	1	1
271.8	SW-6	2006	before	354	77.101	1621.253	182	27.692	1202.522	14	3.928	53.459		2	2	2	0
239.4	SW-2	2005	before	406	88.511	1861.173	39	5.974	259.440	13	3.586	48.801	2210	3	2	2	1
239.4	SW-2	2006	before	508	110.854	2330.999	1	0.152	6.590	11	2.969	40.411		2	2	2	0
236.8	SW-3	2005	before	3571	778.684	16373.916	925	140.309	6092.964	622	168.667	2295.357		2	2	2	0
234.2	SW-4	2005	before	4971	1083.976	22793.512	3937	597.414	25942.840	1493	404.698	5507.472		3	3	3	0
228.2	SW-1	2005	before	3860	841.766	17700.399	1	0.152	6.590	1	0.271	3.689		1	1	1	0
228.2	SW-1	2006	before	487	106.299	2235.213	145	21.938	952.673	13	3.586	48.801		2	2	2	0
211	SW-5	2005	before	720	157.013	3301.629	13	1.920	83.355	1	0.271	3.689		2	2	1	0
211	SW-5	2005	after	19480	4248.085	89327.402	2910	441.593	19176.260					1	1	0	0
163.2	SW-9	2005	before	1415	308.472	6486.451	558	84.673	3676.941	523	141.810	1929.874		3	3	3	0

Median permeability estimates by site and depth
(no temperature corrections)

						permeability (cm/hr)			
rm	location	year	site_code	site_numbe	raking	6 in	12 in	18 in	14 in
228.2	SW-1	2005	a	1	unspecified	3860	1	1	
239.4	SW-2	2005	freeze core	3	unspecified				2210
239.4	SW-2	2005	a	1	unspecified	765	1550	1	
239.4	SW-2	2005	b	2	unspecified	230	1	175	
239.4	SW-2	2005	c	3	unspecified	380			
236.8	SW-3	2005	a	1	unspecified	7370	1660	445	
236.8	SW-3	2005	b	2	unspecified	1730	515	870	
234.2	SW-4	2005	a	1	unspecified	2450	2360	795	
234.2	SW-4	2005	b	2	unspecified	12050	9300	4360	
234.2	SW-4	2005	c	3	unspecified	4160	2780	960	
211	SW-5	2005	a	1	before	405	1		
211	SW-5	2005	a	1	after	19480	2910		
211	SW-5	2005	b	2	unspecified	1280	160	1	
271.8	SW-6	2005	freeze core	3	unspecified				350
271.8	SW-6	2005	a	1	unspecified	4580	285		
271.8	SW-6	2005	b	2	unspecified	1	55.5	310	
278.5	SW-7	2005	a	1	unspecified	1120	330	1	
278.5	SW-7	2005	b	2	unspecified	1540	110	180	
275.8	SW-8	2005	a	1	unspecified	1270	4200	2630	
275.8	SW-8	2005	b	2	unspecified	1	185	1	
163.2	SW-9	2005	a	1	unspecified	2530	415	905	
163.2	SW-9	2005	b	2	unspecified	1980	1820	565	
163.2	SW-9	2005	c	3	unspecified	565	230	280	
278.5	SW-7	2005	c	3	before	2860	285		
278.5	SW-7	2005	c	3	after	2860	180		
278.5	SW-7	2005	d	4	before	3600	485		
278.5	SW-7	2005	d	4	after	11940	415		
278.5	SW-7	2005	e	5	unspecified	1570	120	185	
228.2	SW-1	2006	2006 a	2	unspecified	720	190	1	
228.2	SW-1	2006	2006 b	3	unspecified	330	110	175	
239.4	SW-2	2006	2006 a	5	unspecified	1520	1	120	
239.4	SW-2	2006	2006 b	6	unspecified	170	1	1	
271.8	SW-6	2006	2006 a	4	unspecified	500	120	1	
271.8	SW-6	2006	2006 b	5	unspecified	250	277.5	210	

location SW-9, 2005, site_code "a" was measured at 17.5" rather than 18"
Source file: permeability_070110

Permeability Field Data

date	crew	rm	location	site_code	site_number	raking	depth (in)	repetition	clarity	start height (cm)	end height (cm)	time (s)	comments
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	6	1					aborted; moved head of sipper
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	6	2	0	0	37.5	66	water depth: 16.5 inches
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	6	3	0	0	36	68	photo # 194
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	6	4	0	0	35.7	69	
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	6	5	0	0	34.9	77	
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	6	6	0	0	34.8	64	
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	12	1	1	0	1.1	157	
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	12	2	1	0	1.1	156	
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	12	3	1	0	1.6	154	
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	12	4	0	0	2.2	154	
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	12	5	0	0	1.4	154	
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	18	1					aborted; battery died
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	18	2	2	0	1.5	275	
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	18	3	2	0	1.6	278	
10/18/2005	Cliff, Mike	228.2	SW-1	a	1	unspecified	18	4	2	0	1.5	274	
10/19/2005	Cliff, Russ	239.4	SW-2	freeze core	3	unspecified	14	1	4	0	27.4	90	water depth: 16.25 inches
10/19/2005	Cliff, Russ	239.4	SW-2	freeze core	3	unspecified	14	2	3	0	32.4	95	
10/19/2005	Cliff, Russ	239.4	SW-2	freeze core	3	unspecified	14	3	1	0	29.4	90	
10/19/2005	Cliff, Russ	239.4	SW-2	freeze core	3	unspecified	14	4	1	0	32.4	95	
10/19/2005	Cliff, Russ	239.4	SW-2	freeze core	3	unspecified	14	5	0.5	0	30.2	90	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	6	1	0	0	16.5	120	water depth: 15 inches
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	6	2	0	0	16.2	119	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	6	3	0	0	17.3	119	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	6	4	0	0	15.9	120	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	6	5	0	0	13.2	120	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	12	1	2	0	29.5	120	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	12	2	1	0	29.4	120	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	12	3	1	0	29.6	120	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	12	4	1	0	29.7	120	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	12	5	0	0	30.1	120	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	18	1	3	0	4.8	240	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	18	2	3	0	4.4	240	
10/19/2005	Cliff, Mike	239.4	SW-2	a	1	unspecified	18	3	2	0	4.9	240	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	6	1	2.5	0	7.8	150	downstream of freeze core site on thalweg side
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	6	2	1	0	8.2	150	water depth: 17.5 inches
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	6	3	0	0	7.9	150	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	6	4	0	0	9	150	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	6	5	0	0	6.5	150	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	12	1	3	0	1.8	270	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	12	2	3	0	2.3	270	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	12	3	2	0	2.3	270	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	12	4	1	0	1.7	270	battery running low
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	12						no measurement

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date	crew	rm	location	site_code	site_number	raking	depth (in)	repetition	clarity	start height (cm)	end height (cm)	time (s)	comments
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	18	1	4	0	4.8	150	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	18	2	4	0	5.9	150	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	18	3	4	0	6.4	155	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	18	4	3	0	6.2	150	
10/19/2005	Cliff, Russ	239.4	SW-2	b	2	unspecified	18	5	3	0	6.2	150	
10/19/2005	Cliff, Russ	239.4	SW-2	c	3	unspecified	6	1	2	0	9.2	120	water depth: 25.5 inches
10/19/2005	Cliff, Russ	239.4	SW-2	c	3	unspecified	6	2	0.5	0	8.9	120	
10/19/2005	Cliff, Russ	239.4	SW-2	c	3	unspecified	6	3	0	0	9.3	120	
10/19/2005	Cliff, Russ	239.4	SW-2	c	3	unspecified	6	4	0	0	9.8	120	
10/19/2005	Cliff, Russ	239.4	SW-2	c	3	unspecified	6	5	0	0	10.3	120	
10/19/2005	Cliff, Russ	239.4	SW-2	c	3	unspecified	12	1					aborted; battery died
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	6	1	0.5	0	25	30	water depth: 11 inches
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	6	2	0	0	24	30	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	6	3	0	0	24.3	30	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	6	4	0	0	24.8	30	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	6	5	0	0	24.8	30	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	12	1	4	0	22.8	90	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	12	2	3	0	23.8	90	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	12	3	2	0	23.9	90	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	12	4	2	0	23.8	90	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	12	5	1	0	23.8	89	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	18	1	4	0	11.9	150	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	18	2	4	0	13.5	150	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	18	3	3	0	13	150	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	18	4	2	0	13.2	150	
10/20/2005	Cliff, Evan	236.8	SW-3	a	1	unspecified	18	5					sipper lock slipped; stopped at 4 eps
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	6	1	2	0	16.2	60	water depth: 12 inches
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	6	2	1	0	17.3	60	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	6	3	0.5	0	16.7	60	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	6	4	0	0	17.8	60	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	6	5	0	0	16.5	60	battery at 11.7 V
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	6	6	0	0	13.5	60	changed battery; new battery at 12.5 V
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	6	7	0	0	13.7	60	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	12	1	4	0	14.7	150	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	12	2	3	0	15.1	150	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	12	3	2	0	14.9	150	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	12	4	1.5	0	15.7	150	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	12	5	1	0	14.1	150	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	18	1	5	0	18.6	120	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	18	2	4	0	18.4	120	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	18	3	3.5	0	18.2	120	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	18	4	2	0	18.8	120	
10/20/2005	Cliff, Evan	236.8	SW-3	b	2	unspecified	18	5	1.5	0	18.5	120	

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date	crew	rm	location	site_code	site_number	raking	depth (in)	repetition	clarity	start height (cm)	end height (cm)	time (s)	comments
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	6	1	2	0	21.2	60	water depth: 16 inches
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	6	2	2	0	22.7	60	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	6	3	2	0	22.2	60	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	6	4	1	0	22.4	60	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	6	5	1	0	23.1	60	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	12	1	1	0	21.6	60	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	12	2	1	0	21.7	60	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	12	3	1	0	22	60	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	12	4	0.5	0	21.1	60	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	12	5	0.5	0	20.4	60	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	18	1	4.5	0	17.3	150	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	18	2	3	0	19.5	150	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	18	3	2	0	21	150	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	18	4	1	0	24.3	150	
10/20/2005	Kyle, Evan	234.2	SW-4	a	1	unspecified	18	5	0.5	0	25.1	150	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	6	1	3	0	30	30	water depth: 15 inches
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	6	2	2	0	32.2	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	6	3	1.5	0	30.6	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	6	4	2	0	31.2	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	6	5	1	0	31.1	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	12	1	3	0	27	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	12	2	2	0	28.2	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	12	3	1	0	27	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	12	4	1	0	27.9	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	12	5	1	0	27.1	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	18	1	5	0	29.5	60	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	18	2	4	0	34.4	60	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	18	3	3	0	17.1	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	18	4	3	0	17	30	
10/20/2005	Kyle, Evan	234.2	SW-4	b	2	unspecified	18	5	2	0	18.3	30	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	6	1	2	0	26.3	60	water depth: 16 inches
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	6	2					trial aborted due to a mistake
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	6	3	1	0	33.2	63	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	6	4	0	0	34.8	60	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	6	5	0	0	33.2	60	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	6	6	0	0	33.4	60	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	12	1	3	0	24.7	60	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	12	2	2.5	0	25.3	60	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	12	3	2	0	26.7	60	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	12	4	1	0	25.6	60	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	12	5	0.5	0	26.9	60	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	18	1	4	0	19.4	130	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	18	2	3	0	19.9	130	battery: 10.7 V

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date	crew	rm	location	site_code	site_number	raking	depth (in)	repetition	clarity	start height (cm)	end height (cm)	time (s)	comments
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	18	3	2	0	22.3	130	changed battery: 12.7 V
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	18	4	1	0	21.7	130	
10/20/2005	Cliff, Evan	234.2	SW-4	c	3	unspecified	18	5	0.5	0	22.7	130	
10/21/2005	Cliff, Evan	211	SW-5	a	1	before	6	1	1.5	0	12.4	150	
10/21/2005	Cliff, Evan	211	SW-5	a	1	before	6	2	0	0	12.2	150	
10/21/2005	Cliff, Evan	211	SW-5	a	1	before	6	3	0	0	12.1	150	
10/21/2005	Cliff, Evan	211	SW-5	a	1	before	6	4	0	0	12.3	150	
10/21/2005	Cliff, Evan	211	SW-5	a	1	before	6	5	0	0	11.1	150	
10/21/2005	Cliff, Evan	211	SW-5	a	1	before	12	1	5	0	0.5	390	
10/21/2005	Cliff, Evan	211	SW-5	a	1	before	12	2	4	0	0.8	420	
10/21/2005	Cliff, Evan	211	SW-5	a	1	before	12	3	4	0	1.1	420	
10/21/2005	Cliff, Evan	211	SW-5	a	1	unspecified	12	4					skipped
10/21/2005	Cliff, Evan	211	SW-5	a	1	unspecified	12	5					skipped
10/21/2005	Cliff, Evan	211	SW-5	a	1	after	6	1	0	0	31.1	25	
10/21/2005	Cliff, Evan	211	SW-5	a	1	after	6	2	0	0	30.7	25	
10/21/2005	Cliff, Evan	211	SW-5	a	1	after	6	3	0	0	31.3	25	
10/21/2005	Cliff, Evan	211	SW-5	a	1	after	6	4	0	0	31.8	25	
10/21/2005	Cliff, Evan	211	SW-5	a	1	after	6	5	0	0	31.1	25	
10/21/2005	Cliff, Evan	211	SW-5	a	1	after	12	1	2	0	13.5	30	
10/21/2005	Cliff, Evan	211	SW-5	a	1	after	12	2	0	0	13.3	30	
10/21/2005	Cliff, Evan	211	SW-5	a	1	after	12	3	0	0	13.4	30	
10/21/2005	Cliff, Evan	211	SW-5	a	1	after	12	4	0	0	13.3	30	
10/21/2005	Cliff, Evan	211	SW-5	a	1	after	12	5	0	0	15.3	30	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	6	1	1	0	11.9	60	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	6	2	0	0	12.4	60	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	6	3	0	0	12.3	60	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	6	4	0	0	12.2	60	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	6	5	0	0	12.2	60	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	12	1	5	0	4.7	180	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	12	2	4	0	7	180	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	12	3	3	0	9.4	180	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	12	4	2	0	5.9	180	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	12	5	1	0	8.4	180	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	18	1	5	0	1.6	420	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	18	2	4	0	2.3	300	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	18	3	3	0	2.5	300	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	18	4	2	0	2.3	420	
10/21/2005	Cliff, Evan	211	SW-5	b	2	unspecified	18	5	2	0	2.5	420	
10/22/2005	Cliff, Evan	271.8	SW-6	freeze core	3	unspecified	14	1	4.5	0	11.8	150	
10/22/2005	Cliff, Evan	271.8	SW-6	freeze core	3	unspecified	14	2	4	0	11.2	150	
10/22/2005	Cliff, Evan	271.8	SW-6	freeze core	3	unspecified	14	3	2	0	10.5	150	
10/22/2005	Cliff, Evan	271.8	SW-6	freeze core	3	unspecified	14	4	1	0	10.5	150	
10/22/2005	Cliff, Evan	271.8	SW-6	freeze core	3	unspecified	14	5	0.5	0	11.1	150	

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date	crew	rm	location	site_code	site_number	raking	depth (in)	repetition	clarity	start height (cm)	end height (cm)	time (s)	comments
10/22/2005	Cliff, Evan	271.8	SW-6	a	1	unspecified	6	1	0	0	27.6	45	
10/22/2005	Cliff, Evan	271.8	SW-6	a	1	unspecified	6	2	0	0	27.2	45	
10/22/2005	Cliff, Evan	271.8	SW-6	a	1	unspecified	6	3	0	0	26.4	45	
10/22/2005	Cliff, Evan	271.8	SW-6	a	1	unspecified	6	4	0	0	25.9	45	
10/22/2005	Cliff, Evan	271.8	SW-6	a	1	unspecified	6	5	0	0	25.5	45	
10/22/2005	Cliff, Evan	271.8	SW-6	a	1	unspecified	12	1	0	0	4.8	120	
10/22/2005	Cliff, Evan	271.8	SW-6	a	1	unspecified	12	2	0	0	5.1	125	
10/22/2005	Cliff, Evan	271.8	SW-6	a	1	unspecified	12	3	0	0	8.3	120	
10/22/2005	Cliff, Evan	271.8	SW-6	a	1	unspecified	12	4	0	0	7.5	120	
10/22/2005	Cliff, Evan	271.8	SW-6	a	1	unspecified	12	5	0	0	8.9	120	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	6	1	4	0	4.3	120	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	6	2	3	0	2.9	120	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	6	3	2	0	4	120	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	6	4					skipped
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	6	5	0	0	2.2	120	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	6	6	0	0	3.7	120	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	12	1	4	0	3.3	240	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	12	2	4	0	8	240	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	12	3	3	0	10.1	240	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	12	4	3	0	5.8	240	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	12	5					skipped
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	18	1	5	0	7.4	120	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	18	2	5	0	7.8	120	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	18	3	4	0	8.7	120	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	18	4	3	0	8	120	
10/22/2005	Cliff, Evan	271.8	SW-6	b	2	unspecified	18	5	3	0	8.8	120	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	6	1	3	0	12.3	60	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	6	2	1	0	10.7	60	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	6	3	0	0	10.3	60	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	6	4	0	0	10.7	60	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	6	5	0	0	11.7	60	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	12	1	5	0	7.5	135	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	12	2	5	0	9.8	140	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	12	3	4	0	8.7	135	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	12	4	3	0	9.4	135	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	12	5	3	0	9.7	135	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	18	1	5	0	2.2	210	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	18	2					skipped
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	18	3	5	0	1.8	210	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	18	4	5	0	2.3	210	
10/23/2005	Cliff, Kyle	278.5	SW-7	a	1	unspecified	18	5					skipped
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	6	1	3	0	14.7	60	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	6	2	0	0	12.8	60	

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date	crew	rm	location	site_code	site_number	raking	depth (in)	repetition	clarity	start height (cm)	end height (cm)	time (s)	comments
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	6	3	0	0	16.6	65	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	6	4	0	0	15.2	60	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	6	5	0	0	13.4	60	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	12	1	5	0	4.4	150	slightly less than 12 inches depth
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	12	2	4	0	5.2	158	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	12	3	2	0	5.2	158	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	12	4	2	0	5.9	155	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	12	5	2	0	8.7	155	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	18	1	5	0	5.2	120	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	18	2	5	0	6	120	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	18	3	4	0	5.4	120	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	18	4	3	0	4.6	120	
10/23/2005	Cliff, Kyle	278.5	SW-7	b	2	unspecified	18	5	2	0	4.4	120	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	6	1	4	0	11.3	60	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	6	2	3	0	12.1	60	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	6	3	2	0	11.2	60	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	6	4	2	0	12.5	60	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	6	5	1	0	12.2	60	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	12	1	5	0	23	45	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	12	2	3	0	23.9	45	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	12	3	2	0	25.1	45	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	12	4	2	0	25.3	45	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	12	5	1	0	25.2	45	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	18	1	5	0	21.2	60	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	18	2	3	0	23.1	60	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	18	3	3	0	24.2	60	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	18	4	2	0	26.5	60	
10/23/2005	Cliff, Kyle	275.8	SW-8	a	1	unspecified	18	5	1	0	26.2	60	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	6	1	4	0	3.7	150	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	6	2	3	0	4.3	150	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	6	3	1	0	3.5	150	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	6	4	0	0	4.5	150	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	6	5	0	0	3.7	150	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	12	1	5	0	4.7	120	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	12	2	4	0	5.1	120	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	12	3	4	0	5.3	120	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	12	4	3	0	5.4	120	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	12	5	2	0	5.3	120	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	18	1	5	0	2	180	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	18	2	5	0	1.9	180	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	18	3	4	0	2.7	180	
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	18	4					
10/23/2005	Cliff, Kyle	275.8	SW-8	b	2	unspecified	18	5					

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date	crew	rm	location	site_code	site_number	raking	depth (in)	repetition	clarity	start height (cm)	end height (cm)	time (s)	comments
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	6	1	3	0	22.5	60	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	6	2	2	0	24.2	65	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	6	3	1	0	24.2	60	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	6	4	0.5	0	24.7	60	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	6	5	0.5	0	23.2	60	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	12	1	4	0	7.6	95	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	12	2	3	0	7.8	95	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	12	3	2	0	8.4	95	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	12	4	1	0	7.9	95	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	12	5	1	0	9.4	95	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	17.5	1	5	0	10.8	95	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	17.5	2	3	0	15.2	95	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	17.5	3	2	0	8.7	60	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	17.5	4	1	0	16.3	95	
10/24/2005	Cliff, Evan	163.2	SW-9	a	1	unspecified	17.5	5	0	0	18.5	95	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	6	1	3	0	18.3	60	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	6	2	2	0	18.8	60	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	6	3	1	0	19.6	60	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	6	4	0	0	19.2	60	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	6	5	0	0	18.8	60	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	12	1	4	0	13.4	60	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	12	2	2	0	17.8	65	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	12	3	1	0	17.4	60	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	12	4	1	0	18.7	60	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	12	5	1	0	18	60	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	18	1	4	0	9	90	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	18	2	3	0	9.4	90	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	18	3	2	0	9.6	90	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	18	4	1	0	10.4	90	
10/24/2005	Cliff, Evan	163.2	SW-9	b	2	unspecified	18	5	1	0	4.8	60	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	6	1					
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	6	2	3	0	6.7	70	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	6	3	2	0	6.6	70	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	6	4	1	0	7.5	70	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	6	5	0	0	7.4	70	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	6	6	0	0	7.4	70	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	12	1	4	0	4.7	90	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	12	2	3	0	4.5	90	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	12	3	2	0	4.7	90	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	12	4	1.5	0	4.8	90	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	12	5	1	0	6.1	100	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	18	1	5	0	5.7	120	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	18	2	4	0	7	120	

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date	crew	rm	location	site_code	site_number	raking	depth (in)	repetition	clarity	start height (cm)	end height (cm)	time (s)	comments
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	18	3	3	0	7.3	120	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	18	4	2	0	7.6	120	
10/24/2005	Cliff, Evan	163.2	SW-9	c	3	unspecified	18	5	1	0	7.5	120	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	before	6	1	1	0	23.3	60	15m u/s of bulk sampling site; large subsurf. particles
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	before	6	2	0	0	26.9	60	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	before	6	3	0	0	26.4	60	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	before	6	4	0	0	27.6	60	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	before	6	5	0	0	25.6	60	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	before	12	1	4	0	5.6	90	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	before	12	2	3	0	7.8	95	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	before	12	3	2	0	5.6	90	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	before	12	4	1	0	5.5	90	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	before	12	5	0	0	5.4	90	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	after	6	1	1	0	22	50	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	after	6	2	0	0	24.3	50	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	after	6	3	0	0	21.1	50	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	after	6	4	0	0	27.1	60	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	after	6	5	0	0	25.4	60	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	after	12	1	3	0	3.3	100	large subsurface particles hindered digging
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	after	12	2	3	0	4.2	100	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	after	12	3	4	0	4.3	100	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	after	12	4	1	0	5.2	100	
10/26/2005	Cliff, Koll	278.5	SW-7	c	3	after	12	5	0	0	5.4	100	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	before	6	1	0	0	22.3	45	2 m to bank side of SW-7c
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	before	6	2	0	0	23.9	45	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	before	6	3	0	0	23.6	45	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	before	6	4	0	0	21.5	45	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	before	6	5	0	0	22.9	45	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	before	12	1	3	0	8.2	90	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	before	12	2	2	0	8.5	90	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	before	12	3	1	0	8.9	90	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	before	12	4	0	0	8.3	90	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	before	12	5	0	0	7.8	90	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	after	6	1	0	0	26.8	25	close to the max pumping rate from the standpipe
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	after	6	2	0	0	26.8	25	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	after	6	3	0	0	25.7	25	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	after	6	4	0	0	25.1	25	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	after	6	5	0	0	25.8	25	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	after	12	1	0	0	8.3	90	large subsurface particles hindered digging
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	after	12	2	0	0	9.9	90	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	after	12	3	0	0	6.9	90	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	after	12	4	0	0	7.5	90	
10/26/2005	Cliff, Koll	278.5	SW-7	d	4	after	12	5	0	0	5.9	90	

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date	crew	rm	location	site_code	site_number	raking	depth (in)	repetition	clarity	start height (cm)	end height (cm)	time (s)	comments
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	6	1	1	0	15.3	50	2 m downstream from bulk sample;
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	6	2	0	0	12.9	50	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	6	3	0	0	12.5	50	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	6	4	0	0	11.6	50	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	6	5	0	0	11.2	50	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	12	1	2	0	3.3	100	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	12	2	1	0	4.5	100	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	12	3	0	0	4	100	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	12	4	0	0	3.5	100	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	12	5	0	0	3.5	100	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	18	1	5	0	4.8	90	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	18	2	4	0	3.8	90	V= 11.2
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	18	3	3	0	3.8	90	V= 12.9 (battery changed)
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	18	4	2	0	4	90	
10/26/2005	Cliff, Koll	278.5	SW-7	e	5	unspecified	18	5	1	0	4.2	90	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 a	2	unspecified	6	1	2.5	0	11.6	90	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 a	2	unspecified	6	2	0	0	11.2	90	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 a	2	unspecified	6	3	0	0	12.1	90	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 a	2	unspecified	6	4	0	0	12.5	90	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 a	2	unspecified	6	5	0	0	11.8	90	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 a	2	unspecified	12	1	1	0	5.5	120	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 a	2	unspecified	12	2	1	0	5.6	120	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 a	2	unspecified	12	3	0	0	5.6	120	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 a	2	unspecified	18	1	1	0	4.5	181	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 a	2	unspecified	18	2	1	0	7.2	240	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 b	3	unspecified	6	1	0	0	7.5	75	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 b	3	unspecified	6	2	0	0	5.6	75	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 b	3	unspecified	6	3	0	0	5.2	75	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 b	3	unspecified	6	4	0	0	5.2	75	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 b	3	unspecified	6	5	0	0	4.7	75	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 b	3	unspecified	12	1	1	0	5.1	120	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 b	3	unspecified	12	2	0	0	3.8	120	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 b	3	unspecified	12	3	0	0	4.1	120	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 b	3	unspecified	18	1	2	0	7.2	180	
10/26/2006	Cliff, Koll	228.2	SW-1	2006 b	3	unspecified	18	2	2	0	7.8	180	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	6	1	1	0	14.5	60	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	6	2	0	0	14.5	60	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	6	3	0	0	14.8	60	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	6	4	0	0	14.3	60	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	6	5	0	0	14.2	60	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	12	1	4	0	3.2	150	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	12	2	4	0	3.1	150	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	12	3	3	0	4.4	150	

Permeability Field Data

date	crew	rm	location	site_code	site_number	raking	depth (in)	repetition	clarity	start height (cm)	end height (cm)	time (s)	comments
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	18	1	4	0	4.2	120	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	18	2	4	0	4.2	120	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 a	5	unspecified	18	3	4	0	4.6	120	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 b	6	unspecified	6	1	3	0	4.6	120	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 b	6	unspecified	6	2	2	0	5.1	120	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 b	6	unspecified	6	3	1	0	4.7	120	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 b	6	unspecified	12	1	2.5	0	3.8	300	
10/26/2006	Cliff, Koll	239.4	SW-2	2006 b	6	unspecified	18	1	3	0	0.7	300	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	6	1	4	0	4.9	60	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	6	2	3	0	5.7	60	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	6	3	3	0	5.8	60	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	6	4	2	0	5.6	60	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	6	5	2	0	5.8	60	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	12	1	5	0	4.6	150	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	12	2	4	0	5.2	150	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	12	3					aborted
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	12	4	2	0	5.7	150	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	18	1	5	0	3.2	180	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	18	2	5	0	5.1	180	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 a	4	unspecified	18	3	4	0	6.2	180	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	6	1	5	0	4.2	90	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	6	2	4		5.1	90	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	6	3	3	0	4.9	90	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	6	4	2	0	5.8	90	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	12	1	5	0	5.3	105	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	12	2	5	0	5.9	105	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	12	3	4	0	6.8	105	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	12	4	3	0	7.2	105	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	18	1					aborted
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	18	2					aborted
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	18	3	4	0	4.8	105	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	18	4	3	0	4.7	105	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	18	5	2	0	5.5	105	
10/27/2006	Cliff, Koll	271.8	SW-6	2006 b	5	unspecified	18	6	2	0	6.2	105	

Source file: permeability_070110

Wolman Pebble Counts Phi Scale													
Site name	SWW-1	SWW-2	SWW-3	SWW-4	SWW-5	SWW-6	SWW-7	SWW-8	SWW-9	SWW-10	SWW-11	SWW-12	SWW-13
River mile	298.3	297.2	296.15	294.84	294.33	293	293	292.5	291.5	291.2	289.2	288	286.3
Count 1	6	4	8	7	8	7	6	8	7	8	8	8	8
Count 2	5	7	8	7	6	6	8	8	8	7	8	7	7
Count 3	7	6	7	6	8	7	8	9	8	6	6	7	7
Count 4	8	7	8	8	7	6	8	8	8	7	7	7	6
Count 5	1	5	8	6	5	6	1	8	8	6	8	7	8
Count 6	3	6	8	7	8	7	8	7	8	6	6	6	7
Count 7	8	7	6	7	5	8	6	7	8	6	8	7	8
Count 8	7	5	8	7	7	7	7	8	8	6	8	8	7
Count 9	7	7	8	8	7	1	7	7	9	6	8	7	7
Count 10	7	7	8	8	7	7	8	8	8	7	1	7	7
Count 11	8	7	1	7	4	8	8	9	8	7	8	8	7
Count 12	9	6	8	7	7	7	8	5	8	7	8	7	8
Count 13	7	4	7	8	5	1	6	8	7	6	8	8	7
Count 14	7	7	8	7	6	6	8	8	8	6	6	7	7
Count 15	9	5	5	5	8	6	7	8	8	7	8	7	7
Count 16	8	6	7	7	6	7	7	8	8	7	7	7	8
Count 17	7	6	8	7	8	7	6	7	7	6	7	8	7
Count 18	7	5	9	7	6	7	4	9	8	7	8	7	8
Count 19	9	6	8	6	7	6	5	9	8	7	8	6	8
Count 20	7	5	8	7	7	8	6	8	8	7	7	8	8
Count 21	8	6	7	1	8	8	1	7	8	6	7	7	7
Count 22	7	6	8	6	6	8	1	6	8	8	7	7	7
Count 23	8	7	8	6	7	6	5	7	8	8	7	7	7
Count 24	8	7	8	7	8	7	6	8	8	6	8	7	7
Count 25	8	6	9	6	8	1	8	7	8	7	5	8	7
Count 26	7	6	1	7	6	6	7	7	7	6	6	8	6
Count 27	7	7	8	5	7	7	9	6	8	6	8	8	8
Count 28	7	7	8	7	8	1	8	6	8	8	1	8	7
Count 29	8	6	7	7	9	7	6	8	8	6	8	7	7
Count 30	7	7	3	6	5	7	7	8	8	7	8	6	7
Count 31	8	7	7	5	7	6	6	8	8	7	7	8	7
Count 32	5	7	8	4	6	7	8	7	8	6	8	7	8
Count 33	5	6	7	7	7	6	6	6	9	6	8	7	7
Count 34	5	6	8	7	1	7	9	6	8	7	7	6	8
Count 35	1	6	6	7	8	7	5	8	8	7	8	6	7
Count 36	1	7	7	6	5	3	7	9	7	8	7	7	7
Count 37	3	7	8	8	9	8	8	9	8	7	8	6	7
Count 38	7	6	1	7	6	5	8	8	7	8	7	7	6
Count 39	8	7	3	7	8	8	7	9	7	8	8	7	8
Count 40	1	7	8	8	7	7	6	8	6	8	7	8	8
Count 41	5	3	5	6	7	5	9	8	8	6	6	8	8
Count 42	8	1	6	7	8	6	8	9	8	8	6	8	6
Count 43	6	6	8	5	7	6	6	8	7	7	7	6	8
Count 44	7	1	8	6	6	6	5	8	8	8	8	7	6
Count 45	7	3	8	5	8	8	5	8	8	7	8	7	7
Count 46	7	6	8	7	5	7	6	8	8	5	9	8	6
Count 47	9	6	6	8	8	7	6	5	7	7	8	8	6
Count 48	6	7	4	8	5	6	7	8	7	5	7	7	8
Count 49	9	6	6	6	7	7	6	7	8	7	4	7	7
Count 50	9	6	1	6	7	7	8	8	8	4	7	7	7
Count 51	7	6	7	1	7	5	6	8	8	6	6	8	8
Count 52	7	6	4	7	1	4	5	7	8	7	8	5	7
Count 53	8	6	7	7	6	1	6	8	8	7	7	7	7
Count 54	6	7	7	7	1	5	6	7	7	6	8	8	6
Count 55	8	6	7	7	7	6	8	7	9	6	8	8	5
Count 56	6	7	6	7	6	6	7	8	8	7	6	7	7
Count 57	8	6	7	7	8	6	8	8	8	6	6	7	6
Count 58	8	8	9	9	7	7	9	8	8	4	7	7	7
Count 59	7	5	9	9	6	7	7	7	7	6	8	8	7
Count 60	8	7	8	7	6	6	8	8	6	7	6	8	7
Count 61	5	2	7	6	4	1	8	5	8	8	7	8	8
Count 62	3	6	7	6	8	7	6	8	8	8	7	7	7
Count 63	7	7	7	7	7	7	7	9	8	6	7	7	7
Count 64	8	7	8	7	7	7	8	8	8	7	7	7	8
Count 65	1	7	8	4	7	8	8	8	3	5	7	7	6
Count 66	6	6	1	6	6	8	7	8	8	7	7	7	9
Count 67	1	4	7	7	5	7	8	7	7	7	7	7	8
Count 68	8	7	8	7	7	7	7	7	8	4	8	7	7
Count 69	8	7	8	5	9	7	8	7	8	6	6	7	8
Count 70	5	7	9	7	8	6	8	7	7	6	6	8	8
Count 71	6	6	8	5	9	8	7	7	8	7	7	7	7
Count 72	8	2	5	7	8	8	8	7	8	7	8	8	6
Count 73	8	8	8	7	7	7	8	7	8	7	1	7	8
Count 74	8	8	6	6	6	6	7	7	8	6	7	4	8
Count 75	9	8	8	5	8	1	8	8	8	6	8	7	7
Count 76	8	7	7	7	7	1	8	8	8	7	7	7	7
Count 77	9	6	6	7	7	1	7	9	8	6	7	8	8
Count 78	8	6	7	6	6	4	7	9	8	7	8	7	7
Count 79	8	5	6	6	6	6	7	8	8	6	6	8	8
Count 80	6	7	6	7	7	7	8	7	8	7	8	7	7
Count 81	5	7	8	7	1	6	1	8	7	7	7	7	8
Count 82	6	6	8	8	1	7	8	8	7	7	7	7	7
Count 83	7	6	8	6	7	5	8	8	7	8	7	8	8
Count 84	6	7	1	7	6	7	7	9	5	7	7	7	7
Count 85	8	7	7	5	6	5	8	8	8	6	6	7	5
Count 86	8	7	5	7	7	8	8	8	8	7	7	7	7
Count 87	7	6	7	7	8	1	8	8	8	7	7	7	8
Count 88	7	6	4	5	4	6	8	8	8	7	7	7	7
Count 89	6	7	7	7	7	6	8	7	8	7	7	8	8
Count 90	8	6	7	6	7	8	8	7	8	7	7	7	6
Count 91	8	7	7	3	7	8	8	8	8	7	8	8	5
Count 92	7	5	7	7	5	8	6	7	8	6	7	7	6
Count 93	8	6	5	7	7	7	5	7	8	7	7	6	7
Count 94	7	6	5	7	8	6	8	8	7	7	8	6	8
Count 95	8	6	9	7	6	7	8	7	8	6	6	8	5
Count 96	7	6	9	7	6	7	8	7	8	7	7	8	7
Count 97	8	6	7	7	8	8	5	8	7	8	7	8	7
Count 98	8	7	5	5	7	1	8	7	7	6	7	7	8
Count 99	7	6	8	7	1	7	7	8	8	7	7	7	8
Count 100	8	8	6	6	8	8	1	7	7	6	7	7	7
binned by	SWW-1	SWW-2	SWW-3	SWW-4	SWW-5	SWW-6	SWW-7	SWW-8	SWW-9	SWW-10	SWW-11	SWW-12	SWW-13
Neg phi	298.3	297.2	296.15	294.84	294.33	293	293	292.5	291.5	291.2	289.2	288	286.3
10	0	0	0	0	0	0	0	0	0	0	0	0	0
9	8	0	7	2	4	0	4	12	3	0	1	0	1
8	35	5	38	9	23	18	42	49	72	14	35	32	33
7	29	37	26	52	34	37	21	31	21	46	44	57	49
6	11	41	11	21	21	25	19	5	2	34	15	9	13
5	8	8	7	11	9	6	8	3	1	3	1	1	4
4	0	3	3	2	3	2	1	0	0	3	1	1	0
3	3	2	2	1	0	1	0	0	1	0	0	0	0
2	0	2	0	0	0	0	0	0	0	0	0	0	0
1	6	2	6	2	6	11	5	0	0	0	3	0	0
Percent finer	SWW-1	SWW-2	SWW-3	SWW-4	SWW-5	SWW-6	SWW-7	SWW-8	SWW-9	SWW-10	SWW-11	SWW-12	SWW-13
Neg phi	298.3	297.2	296.15	294.84	294.33	293	293	292.5	291.5	291.2	289.2	288	286.3
10	100	100	100	100	100	100	100	100	100	100	100	100	100
9	100	100	100	100	100	100	100	100	100	100	100	100	100
8	92	100	93	98	96	100	96	88	97	100	99	100	99
7	57	95	55	89	73	82	54	39	25	86	64	68	66
6	28	58	29	37	39	45	33	8	4	40	20	11	17
5	17	17	18	16	18	20	14	3	2	6	5	2	4
4	9	9	11	5	9	14	6	0	1	3	4	1	0
3	9	6	8	3	6	12	5	0	1	0	3	0	0
2	6	4	6	2	6	11	5	0	0	0	3	0	0
1	6	2	6	2	6	11	5	0	0	0	3	0	0

Wolman Pebb		Wolman Pebble Counts Phi Scale													
Site name	SWW-14	SWW-15	SWW-16	SWW-17	SW-7	SW-8	SW-6	SW-2	SW-3	SW-4	SW-1	SW-5	SW-9	SW-10	
River mile	282.6	281.8	280.1	279.1	278.5	275.8	271.8	239.4	236.8	234.2	228.2	211	163.2	273.5	
Count 1	8	6	6	7	7	7	7	7	6	5	6	7	4	2	
Count 2	7	6	7	8	7	7	5	7	6	6	6	6	7	2	
Count 3	7	5	8	7	7	4	1	7	6	6	6	5	5	2	
Count 4	7	5	7	7	7	7	5	5	7	5	7	6	6	2	
Count 5	8	6	7	7	7	8	7	6	6	7	7	4	4	3	
Count 6	8	7	8	8	6	8	8	7	7	7	6	7	6	3	
Count 7	8	5	7	7	7	3	8	6	7	7	8	6	5	4	
Count 8	7	8	5	7	7	8	6	7	4	6	8	6	3	4	
Count 9	5	7	5	8	6	7	6	7	6	7	7	7	7	4	
Count 10	8	7	8	8	7	7	8	6	7	5	5	7	6	5	
Count 11	6	7	7	8	8	8	5	6	6	5	1	6	4	5	
Count 12	6	7	8	7	8	3	7	6	5	4	6	7	5	5	
Count 13	7	6	7	7	7	6	8	7	5	6	7	7	7	5	
Count 14	7	6	8	7	6	7	8	6	6	4	6	7	5	6	
Count 15	6	7	6	6	7	7	1	2	6	6	7	7	3	6	
Count 16	8	6	7	7	8	8	8	6	7	7	6	6	4	6	
Count 17	7	6	8	7	7	5	8	5	1	3	5	7	6	6	
Count 18	7	7	7	7	8	2	7	7	2	7	6	3	6	6	
Count 19	8	6	7	7	6	8	7	7	4	6	6	7	6	6	
Count 20	7	1	8	7	5	6	6	6	5	7	7	5	2	6	
Count 21	7	7	8	7	8	8	6	7	6	5	6	6	7	6	
Count 22	8	7	7	6	8	7	4	7	6	3	7	5	6	6	
Count 23	6	6	8	7	6	6	8	7	4	6	7	7	6	6	
Count 24	7	7	6	6	8	8	7	7	7	5	6	7	5	6	
Count 25	8	7	8	6	7	8	7	5	5	5	6	5	5	6	
Count 26	6	1	8	7	7	1	1	7	6	6	7	6	6	6	
Count 27	4	5	6	7	6	6	8	6	3	7	6	7	5	6	
Count 28	7	6	7	7	7	5	7	6	5	5	6	5	6	6	
Count 29	7	7	8	7	8	5	7	5	6	6	6	5	3	6	
Count 30	6	7	7	6	8	8	4	5	7	5	6	6	6	6	
Count 31	7	7	8	7	6	7	7	8	6	1	7	7	5	6	
Count 32	9	7	8	1	7	7	6	7	3	5	4	4	6	6	
Count 33	7	7	7	7	8	8	3	6	7	8	6	5	6	6	
Count 34	7	6	7	8	7	7	8	7	6	5	7	7	6	6	
Count 35	7	7	8	8	7	7	7	6	6	5	7	6	6	6	
Count 36	4	4	8	7	7	6	5	7	7	5	5	7	5	6	
Count 37	7	1	7	8	6	5	7	7	6	4	7	3	5	6	
Count 38	7	7	7	1	8	5	5	6	7	1	6	6	5	6	
Count 39	8	6	7	6	8	6	7	5	5	4	7	7	6	6	
Count 40	6	5	7	8	7	1	6	6	7	3	6	5	5	7	
Count 41	7	6	8	7	7	7	7	6	7	3	5	5	6	7	
Count 42	7	6	7	8	8	7	6	6	8	6	7	7	3	7	
Count 43	8	7	6	8	7	8	5	6	3	4	7	6	6	7	
Count 44	6	6	7	7	8	7	1	1	6	5	5	3	3	7	
Count 45	1	6	6	7	7	7	7	5	6	2	6	6	6	7	
Count 46	6	8	8	7	8	6	7	5	2	7	6	5	7	7	
Count 47	5	6	7	1	1	8	6	5	4	5	5	6	4	7	
Count 48	8	1	8	8	8	7	7	5	6	5	6	6	5	7	
Count 49	5	6	8	8	7	6	7	5	6	6	8	6	5	7	
Count 50	7	1	7	7	7	7	7	7	6	7	7	6	7	7	
Count 51	7	6	7	8	7	7	7	7	5	5	7	6	6	7	
Count 52	7	6	8	4	8	7	4	7	6	6	6	7	5	7	
Count 53	8	5	7	7	6	7	7	6	3	4	6	6	5	7	
Count 54	7	6	7	7	3	8	5	5	7	5	8	6	6	7	
Count 55	7	7	7	7	8	7	5	6	6	5	8	6	6	7	
Count 56	6	7	6	5	7	8	7	7	6	5	4	6	6	7	
Count 57	6	7	7	7	6	7	8	6	6	7	8	5	6	7	
Count 58	7	6	7	7	7	7	6	4	3	7	8	5	6	7	
Count 59	4	6	7	6	7	7	6	7	7	5	1	7	5	7	
Count 60	6	5	8	7	8	7	7	1	6	7	6	6	5	7	
Count 61	8	6	7	7	8	7	8	6	7	7	6	6	6	7	
Count 62	8	4	7	6	5	7	7	6	7	7	6	6	6	7	
Count 63	7	6	6	1	8	7	6	1	6	5	7	5	4	7	
Count 64	4	6	7	6	5	7	8	5	6	6	6	4	7	7	
Count 65	6	7	5	7	8	7	1	7	6	7	7	6	6	7	
Count 66	6	7	7	1	8	5	8	7	7	4	4	6	7	7	
Count 67	6	7	6	7	6	6	7	3	1	7	1	3	1	7	
Count 68	1	7	8	7	3	8	8	6	4	5	6	6	1	7	
Count 69	7	7	8	4	8	7	7	7	8	6	6	5	6	7	
Count 70	8	1	7	8	8	7	7	7	5	5	5	7	1	7	
Count 71	6	6	8	8	8	3	6	5	6	7	4	7	6	7	
Count 72	8	6	7	7	5	7	7	7	4	6	6	5	6	7	
Count 73	7	5	8	6	8	7	7	6	5	6	7	6	6	7	
Count 74	7	5	8	8	6	4	6	7	1	4	3	6	6	7	
Count 75	7	5	6	8	6	6	8	8	4	3	6	6	7	7	
Count 76	8	7	8	7	7	8	6	7	4	7	6	6	6	7	
Count 77	5	7	7	7	5	6	4	6	5	5	6	7	6	7	
Count 78	6	7	8	8	6	4	7	6	5	5	5	1	6	7	
Count 79	8	6	8	6	6	7	6	8	7	6	6	5	6	7	
Count 80	6	6	5	6	6	7	7	6	5	7	7	7	7	7	
Count 81	7	6	8	7	6	6	6	7	6	4	6	5	3	7	
Count 82	6	5	8	8	7	6	7	7	4	7	7	7	1	8	
Count 83	1	7	7	8	7	8	5	6	7	3	6	2	6	8	
Count 84	7	7	8	7	5	7	5	7	7	7	6	6	5	8	
Count 85	6	1	7	8	6	6	6	7	6	6	7	3	5	8	
Count 86	8	6	8	7	8	8	5	4	5	4	7	5	6	8	
Count 87	6	7	7	6	6	6	7	7	6	5	7	7	6	8	
Count 88	6	4	7	6	8	8	8	7	5	7	7	6	6	8	
Count 89	5	7	8	9	8	6	7	6	7	5	7	6	6	8	
Count 90	8	7	7	7	8	7	7	6	6	3	7	7	6	8	
Count 91	5	7	8	7	8	6	7	7	5	5	6	6	6	8	
Count 92	7	5	8	8	6	7	5	7	6	4	4	4	4	8	
Count 93	7	7	8	8	7	7	6	7	5	7	6	7	5	8	
Count 94	7	6	7	7	8	6	7	7	3	4	7	6	5	8	
Count 95	6	7	7	7	4	7	7	5	7	6	8	6	5	8	
Count 96	8	7	6	8	1	8	1	7	5	7	6	6	5	8	
Count 97	6	6	7	6	5	6	7	4	7	6	7	3	6	8	
Count 98	7	6	7	7	6	6	7	7	7	7	5	6	6	8	
Count 99	8	1	7	8	1	8	7	7	8	7	6	6	5	8	
Count 100	7	3	6	7	6	7	8	6	6	5	7	6	5	8	
binned by	SWW-14	SWW-15	SWW-16	SWW-17	SW-7	SW-8	SW-6	SW-2	SW-3	SW-4	SW-1	SW-5	SW-9	SW-10	
Neg phi	282.6	281.8	280.1	279.1	278.5	275.8	271.8	239.4	236.8	234.2	228.2	211	163.2	273.5	
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9	1	0	0	1	0	0	0	0	0	0	0	0	0	0	
8	23	2	38	26	33	22	18	3	3	1	8	0	0	19	
7	39	39	46	50	32	43	41	43	24	27	32	28	10	42	
6	24	35	12	15	22	20	18	31	36	20	42	42	46	26	
5	6	12	4	1	7	6	12	15	17	30	9	18	26	4	
4	4	3	0	2	1	3	4	3	9	12	5	4	7	3	
3	0	1	0	0	2	3	1	1	6	7	1	6	6	2	
2	0	0	0	0	0	1	0	1	2	1	0	1	1	4	
1	3	8	0	5	3	2	6	3	3	2	3	1	4	0	
Percent finer	SWW-14	SWW-15	SWW-16	SWW-17	SW-7	SW-8	SW-6	SW-2	SW-3	SW-4	SW-1	SW-5	SW-9	SW-10	
Neg phi	282.6	281.8	280.1	279.1	278.5	275.8	271.8	239.4	236.8	234.2	228.2	211	163.2	273.5	
10	100	100	100	100	100	100	100	100	100	100	100	100	100	100	
9	100	100	100	100	100	100	100	100	100	100	100	100	100	100	512
8	99	100	100	99	100	100	100	100	100	100	100	100	100	100	256
7	76	98	62	73	67	78	82	97	97	99	92	100	100	81	128
6	37	59	16	23	35	35	41	54	73	72	60	72	90	39	64
5	13	24	4	8	13	15	23	23	37	52	18	30	44	13	32
4	7	12	0	7	6	9	11	8	20	22	9	12	18	9	16
3	3	9	0	5	5	6	7	5	11	10	4	8	11	6	8
2	3	8	0	5	3	3	6	4	5	3	3	2	5	4	4
1	3	8	0	5	3	2	6	3	3	2	3	1	4	0	2

Wolman Pebble Count Data (sorted)

Sorted	SWW-1	SWW-2	SWW-3	SWW-4	SWW-5	SWW-6	SWW-7	SWW-8	SWW-9	SWW-10	SWW-11	SWW-12	SWW-13
	298.3	297.2	296.15	294.84	294.33	293	293	292.5	291.5	291.2	289.2	288	286.3
Count 1	2	2	2	2	2	2	2	25	5	8	2	8	22
Count 2	2	2	2	2	2	2	2	25	25	13	2	18	22
Count 3	2	3	2	7	2	2	2	27	35	15	2	34	27
Count 4	2	3	2	8	2	2	2	35	50	18	15	40	30
Count 5	2	4	2	12	2	2	2	45	70	25	20	42	32
Count 6	2	7	2	17	2	2	12	45	70	30	35	42	35
Count 7	6	9	4	17	9	2	17	55	75	33	35	44	35
Count 8	6	12	5	18	15	2	18	55	75	35	38	56	35
Count 9	7	14	10	18	15	2	22	65	75	35	40	62	39
Count 10	18	18	10	20	17	2	25	65	75	35	42	62	40
Count 11	18	20	10	23	18	2	25	70	80	36	45	63	45
Count 12	20	23	20	25	18	4	25	70	84	37	48	64	45
Count 13	25	26	20	28	25	12	30	75	85	39	50	67	45
Count 14	27	28	25	28	25	15	30	75	90	40	52	68	55
Count 15	30	29	25	29	25	16	32	80	90	40	55	72	55
Count 16	30	29	25	30	25	22	35	80	90	42	55	72	55
Count 17	30	29	30	32	28	25	35	85	105	42	55	73	63
Count 18	38	32	30	33	30	25	40	85	115	42	55	75	65
Count 19	40	33	35	37	32	28	40	85	115	44	60	75	65
Count 20	48	33	35	39	32	30	40	85	115	45	63	75	65
Count 21	50	36	37	40	33	32	40	85	123	45	70	77	70
Count 22	50	37	40	43	35	32	40	90	125	50	70	77	70
Count 23	52	37	40	43	35	34	43	90	125	50	73	77	70
Count 24	53	38	50	44	35	35	45	95	125	50	75	78	73
Count 25	60	38	50	45	37	37	48	95	125	53	75	80	75
Count 26	60	39	50	45	38	37	53	95	130	54	75	80	75
Count 27	60	40	55	49	40	38	55	105	135	55	75	85	75
Count 28	63	40	60	49	42	38	55	105	135	56	78	85	80
Count 29	64	41	60	49	45	40	55	105	137	58	80	87	85
Count 30	65	42	65	50	45	41	55	110	145	58	80	88	85
Count 31	66	42	70	50	45	42	60	110	145	58	80	88	85
Count 32	70	42	75	53	45	42	62	110	145	59	80	88	85
Count 33	70	43	75	54	47	44	63	110	145	59	85	90	86
Count 34	72	45	80	59	50	45	65	115	145	60	90	90	88
Count 35	74	46	85	60	50	49	68	115	148	60	93	90	90
Count 36	75	47	90	60	55	49	70	115	150	60	95	92	90
Count 37	75	47	95	62	60	50	70	115	150	62	95	92	91
Count 38	76	47	95	65	60	50	73	120	150	63	95	95	95
Count 39	78	48	100	67	62	50	75	122	150	63	95	98	95
Count 40	85	50	100	67	65	52	75	130	150	63	95	98	95
Count 41	85	50	105	67	65	52	80	130	150	65	97	98	95
Count 42	85	51	105	68	65	54	85	130	155	68	98	98	95
Count 43	86	52	110	69	70	54	90	130	155	70	100	98	95
Count 44	90	52	110	69	73	62	95	130	155	70	101	98	100
Count 45	92	52	115	72	73	63	95	130	156	70	105	98	100
Count 46	95	52	115	75	75	65	95	130	158	70	105	100	100
Count 47	95	53	115	77	75	67	97	135	158	72	105	100	102
Count 48	100	53	115	78	75	69	100	135	160	73	105	102	104
Count 49	110	53	120	80	77	69	105	135	165	73	110	105	105
Count 50	110	54	120	80	80	69	105	140	165	75	110	108	105
Count 51	113	55	125	80	83	70	115	140	165	75	110	110	105
Count 52	115	56	125	82	83	73	117	145	165	76	110	110	105
Count 53	115	57	125	82	85	74	118	145	165	77	110	111	110
Count 54	125	57	125	82	85	75	123	150	165	82	115	115	110
Count 55	125	58	125	85	85	75	130	155	167	82	115	115	115
Count 56	125	58	135	85	85	75	130	155	170	84	117	115	115
Count 57	126	63	135	85	85	75	135	155	172	85	120	115	115
Count 58	132	63	140	86	89	78	135	160	173	85	120	115	117
Count 59	135	66	145	88	92	78	135	160	174	87	120	115	120
Count 60	140	67	145	90	92	82	135	160	175	87	120	118	120
Count 61	140	67	145	90	94	83	135	165	175	87	123	118	125
Count 62	143	67	150	92	95	84	145	165	175	88	125	118	125
Count 63	145	68	150	93	97	86	145	165	180	90	125	120	125
Count 64	145	68	155	95	97	87	145	165	180	90	125	125	125
Count 65	150	69	155	96	110	89	145	165	183	92	130	125	125
Count 66	156	70	160	97	110	95	150	165	183	92	135	125	126
Count 67	158	73	160	97	115	97	150	165	185	94	135	125	130
Count 68	165	73	165	98	115	100	153	170	185	94	137	125	135
Count 69	165	77	165	100	115	100	155	170	185	98	140	130	135
Count 70	165	77	165	100	115	102	155	175	190	103	140	130	135
Count 71	165	78	170	100	120	102	155	180	190	105	145	130	140
Count 72	166	79	175	101	120	103	160	180	193	105	145	132	143
Count 73	168	79	175	102	125	105	163	180	195	110	150	133	145
Count 74	173	79	180	103	135	109	165	185	195	110	150	133	149
Count 75	175	81	180	107	140	115	165	185	195	110	155	137	150
Count 76	176	82	185	110	140	118	168	190	195	110	165	140	150
Count 77	185	82	190	111	140	119	168	190	198	110	165	140	158
Count 78	185	90	195	113	143	120	170	195	200	113	170	145	160
Count 79	186	92	200	113	145	120	175	205	200	115	170	145	160
Count 80	188	93	200	114	148	120	175	205	203	115	173	145	160
Count 81	197	94	205	115	150	122	175	205	205	115	175	148	165
Count 82	198	95	205	115	155	123	175	220	205	118	175	148	165
Count 83	200	96	210	119	155	135	180	220	205	125	183	153	170
Count 84	218	97	210	120	160	145	180	230	205	125	185	155	170
Count 85	220	98	215	120	173	145	183	235	205	125	190	156	170
Count 86	225	98	215	123	195	150	183	240	210	125	190	156	170
Count 87	226	100	217	125	197	152	185	255	215	130	193	157	175
Count 88	227	104	220	125	200	153	185	255	215	130	195	158	175
Count 89	238	106	227	127	210	155	190	260	215	135	198	160	180
Count 90	240	111	230	129	215	165	205	260	220	135	203	160	185
Count 91	245	111	235	130	215	175	205	265	230	135	205	160	185
Count 92	255	115	240	130	235	180	215	270	235	140	207	165	187
Count 93	256	115	255	140	240	185	220	290	235	147	210	165	190
Count 94	256	123	256	145	245	190	225	300	235	150	210	170	200
Count 95	256	127	260	148	245	200	242	310	240	150	215	180	215
Count 96	256	131	260	165	255	213	245	320	245	157	225	185	220
Count 97	256	132	260	192	273	215	275	320	250	160	233	200	225
Count 98	256	170	295	205	279	215	295	335	260	175	240	210	230
Count 99	256	173	300	256	295	225	300	350	260	175	240	245	230
Count 100	256	225	310	260	345	225	305	360	335	200	258	245	295

source file: 2005 Sacramento River grain size results.xls

Wolman Pebble Count Data (sorted)

Sorted	SWW-14	SWW-15	SWW-16	SWW-17	SW-7	SW-8	SW-6	SW-2	SW-3	SW-4	SW-1	SW-5	SW-9	SW-10
	282.6	281.8	280.1	279.1	278.5	275.8	271.8	239.4	236.8	234.2	228.2	211	163.2	273.5
Count 1	2	2	25	2	2	2	2	2	2	2	2	2	2	2
Count 2	2	2	25	2	2	2	2	2	2	2	2	3	2	2
Count 3	2	2	30	2	2	3	2	2	2	3	2	4	2	2
Count 4	12	2	30	2	5	4	2	3	3	4	6	5	2	2
Count 5	15	2	45	2	7	5	2	7	3	4	8	6	3	4
Count 6	15	2	47	15	13	7	2	8	4	6	10	7	4	7
Count 7	15	2	52	15	16	9	4	13	4	6	12	7	5	10
Count 8	22	2	55	30	19	10	10	14	5	7	13	7	5	13
Count 9	22	5	55	34	22	12	12	18	5	7	15	8	7	14
Count 10	25	10	55	35	22	18	12	18	6	7	18	8	7	17
Count 11	30	12	55	40	29	19	15	18	6	9	18	15	7	26
Count 12	30	12	57	40	29	21	18	22	8	9	18	15	8	27
Count 13	30	18	59	40	31	21	20	23	9	9	19	16	9	30
Count 14	32	20	60	40	32	23	20	23	12	9	20	16	9	32
Count 15	33	21	62	40	33	26	22	24	12	11	25	17	10	40
Count 16	33	22	62	45	33	33	22	25	13	11	25	18	13	42
Count 17	35	22	65	45	34	37	22	25	13	11	26	19	14	43
Count 18	35	23	70	48	35	37	23	26	14	11	30	19	15	45
Count 19	40	25	70	50	36	40	25	26	15	12	32	20	16	48
Count 20	40	27	70	50	36	42	25	29	15	12	34	20	16	48
Count 21	40	28	75	50	37	45	28	29	17	13	34	22	16	49
Count 22	40	28	80	60	39	46	28	31	17	14	35	22	18	50
Count 23	42	29	80	62	42	46	31	31	18	16	35	25	18	50
Count 24	45	30	80	65	48	51	32	32	18	17	38	26	19	50
Count 25	49	32	85	68	51	53	32	34	19	17	38	26	19	50
Count 26	50	33	85	70	52	55	35	35	20	18	40	27	20	52
Count 27	50	34	85	73	54	56	42	36	20	19	40	27	20	52
Count 28	50	34	87	75	55	56	45	36	25	19	41	27	20	55
Count 29	52	34	88	75	60	57	50	38	26	19	42	28	21	55
Count 30	53	35	88	75	60	58	50	39	26	19	42	29	21	55
Count 31	55	35	89.5	80	60	58	50	40	26	21	43	32	22	56
Count 32	57	35	90	80	60	58	53	42	27	21	45	32	22	56
Count 33	60	36	95	80	62	63	55	46	27	22	45	32	22	56
Count 34	60	36	95	80	63	63	55	47	27	22	45	35	23	59
Count 35	60	39	95	80	63	63	55	48	27	22	45	35	23	60
Count 36	60	40	98	82	65	64	58	48	27	22	45	35	24	60
Count 37	63	40	98	85	68	67	58	49	30	22	45	36	24	60
Count 38	65	40	100	85	73	71	58	49	32	22	45	36	24	62
Count 39	65	42	100	90	74	72	60	51	32	22	48	36	25	62
Count 40	65	45	100	90	75	74	60	52	33	23	48	37	25	64
Count 41	65	45	100	90	75	77	62	53	33	23	48	38	27	65
Count 42	65	45	100	90	75	79	64	53	34	23	48	38	29	65
Count 43	65	45	100	90	76	82	65	54	34	25	49	40	30	66
Count 44	68	47	105	95	80	84	70	55	35	26	50	41	31	69
Count 45	68	50	105	95	80	84	73	56	35	27	50	41	32	70
Count 46	69	52	110	95	80	85	73	57	35	27	50	42	33	70
Count 47	70	52	110	95	85	88	77	57	36	28	51	42	34	75
Count 48	70	53	110	95	88	89	77	57	37	28	55	44	34	75
Count 49	70	55	110	95	90	92	78	58	38	28	55	45	35	77
Count 50	70	55	115	98	92	93	80	59	39	29	55	47	35	77
Count 51	72	55	115	100	93	93	80	59	40	29	55	48	36	80
Count 52	73	55	115	100	94	95	86	63	43	31	56	48	36	80
Count 53	75	55	115	103	96	96	89	63	43	32	57	49	36	82
Count 54	75	58	120	105	100	98	92	63	44	32	57	50	37	87
Count 55	80	60	120	105	100	98	92	65	45	38	58	50	37	88
Count 56	80	60	120	105	105	98	93	66	46	39	58	50	38	90
Count 57	85	60	120	110	105	99	95	66	46	44	60	51	39	90
Count 58	87	61	120	110	110	100	97	68	47	44	60	52	39	92
Count 59	88	62	122	110	112	102	100	68	47	45	62	52	39	92
Count 60	93	66	125	110	114	103	100	69	48	45	63	52	40	92
Count 61	95	67	125	110	115	107	100	69	48	47	64	53	41	95
Count 62	99	68	127	110	117	109	105	70	52	49	65	55	41	95
Count 63	100	70	129	115	118	109	108	73	52	50	65	55	42	95
Count 64	105	70	130	115	120	112	109	76	53	50	65	56	42	96
Count 65	105	71	130	115	123	112	111	78	53	51	65	56	43	97
Count 66	110	71	135	115	125	114	112	78	54	52	66	57	43	100
Count 67	110	72	135	115	125	115	112	79	55	55	68	58	44	105
Count 68	115	72	135	120	130	116	115	79	55	58	70	59	45	105
Count 69	115	73	135	125	130	118	115	80	56	59	72	59	45	105
Count 70	118	73	142	125	130	118	115	81	57	60	75	60	46	105
Count 71	120	75	145	125	130	119	115	84	60	60	75	61	46	106
Count 72	120	75	145	125	132	121	120	84	62	62	75	63	48	107
Count 73	123	75	145	127	133	122	120	86	63	64	76	64	48	111
Count 74	123	75	153	142	134	122	120	87	64	64	78	64	50	115
Count 75	125	77	155	145	135	122	120	90	65	66	78	65	51	117
Count 76	125	77	155	145	135	126	120	90	65	67	80	68	52	120
Count 77	130	78	158	150	135	127	120	91	67	67	82	70	52	120
Count 78	131	79	160	155	136	127	123	92	72	68	84	70	53	125
Count 79	132	80	160	155	141	129	125	93	73	68	85	71	54	125
Count 80	133	82	160	155	145	130	125	93	73	68	85	72	55	125
Count 81	135	83	165	155	147	133	125	93	74	70	86	72	55	127
Count 82	140	84	165	156	150	135	125	96	75	71	87	74	55	130
Count 83	145	85	165	160	150	137	128	96	77	74	90	74	56	132
Count 84	153	88	165	160	150	138	128	96	78	74	93	74	57	134
Count 85	155	88	165	160	155	140	129	97	78	75	97	74	57	142
Count 86	165	88	170	160	158	142	135	98	78	79	98	75	58	145
Count 87	170	88	173	165	160	148	135	100	79	79	98	80	58	145
Count 88	175	94	175	167	160	150	135	102	83	79	105	82	60	146
Count 89	175	95	175	170	165	151	143	103	87	79	107	85	60	147
Count 90	180	95	178	175	175	157	145	103	88	80	112	86	61	150
Count 91	180	100	180	180	175	165	145	105	90	88	115	87	64	150
Count 92	180	100	183	180	177	165	146	109	92	89	123	90	66	152
Count 93	185	100	185	180	177	165	147	113	95	91	128	93	66	152
Count 94	186	106	185	195	180	173	147	116	97	93	130	93	68	153
Count 95	195	110	195	200	180	188	155	121	107	93	138	96	70	155
Count 96	195	119	200	203	180	195	160	122	110	100	145	99	74	155
Count 97	215	125	200	220	189	201	163	125	125	100	163	100	77	155
Count 98	225	125	200	240	194	223	180	136	132	105	183	101	85	155
Count 99	245	130	205	255	220	252	186	143	138	123	186	105	94	180
Count 100	275	150	210	270	223	255	187	145	165	140	200	107	105	195

source file: 20

2005 Wolman Pebble Count Site Notes

Date	Name	RM	Analog to...	Start Time	End Time	Crew	Northing	Easting	Notes
10/25/2005	SWW-1	298.3	SBG-8	9:18	9:35	CSR, KYB	551477	4493717	Under bridge; just upstream (15 m) of bridge pier; river left. Koll suspects this deposit may be relict of gravel augmentation. Much less coarse near shore; did grid ~ 10 pace x 10 pace.
10/25/2005	SWW-2	297.2	SBG-10	10:10	10:24	CSR, KYB	553357	4493570	RM 297.2; Just downstream of side channel. Marker quartz abundant - gravel from augmentation.
10/25/2005	SWW-3	296.15	SR-93	10:40	11:05	CSR, KYB	553400	4492822	Downstream of RTE 299 bridge, mid-channel island; River right (mainstem side) no evidence of augmented gravel here; Head of riffle, head of bar, flow = 6500 cfs.
10/25/2005	SWW-4	294.84	SR-11 a and b	11:25		CSR, KYB	552827	4491339	Downstream of Cypress Br.; River right; 1980 WC site just downstream of creek outlet. A few quartz pebbles (augmented).
10/25/2005	SWW-5	294.33	SR-12	12:01	12:22	CSR, KYB	552847	4490633	1980 WC site; Opposite bank is rip-rapped and not rip-rapped alternatively; Head of riffle, head of point bar.
10/25/2005	SWW-6	293	SR-13	12:45	13:05	CSR, KYB	552951	4488830	RM 293.0L; 1980 WC site; some quartz; Head of riffle, head of point bar; Koll: "May have been deeply submerged under 7000 cfs" (curently 6500 cfs).
10/25/2005	SWW-7	293	SR-13	13:10		CSR, KYB	552977	4488713	RM 293.0L; 200 feet d/s of SWW-6, looks coarser; Key embedded: 180
10/25/2005	SWW-8	292.5	SBG-9	13:44	14:12	CSR, KYB	553899	4488225	SBG 9 1980 Bulk sampling site.
10/25/2005	SWW-9	291.5	SBG-5	14:35	14:50	CSR, KYB	554691	4486936	RM 291.5L; Just downstream of apex of bend; 1980 BS site; No WC here?
10/25/2005	SWW-10	291.2	SR-19	15:15	15:35	CSR, KYB	554344	4486857	RM 291.2L; Finer than SWW-9; Looks like gravel from Tobiasson injection may be held here; Backwater from side channel (nearly filled) may contribute to deposition. 1980 WC site SR-19; Koll: "Riffle has moved upstream ~30 m".
10/25/2005	SWW-11	289.2	SR-24	15:55	16:07	CSR, KYB	553811	4484198	RM 289.2L; Side channel to left used to be side channel attests to lots of change here; Analog to 1980 WC sites: SR24, 25, 28, 27, 26, 29.
10/25/2005	SWW-12	288	SR-30	16:27	16:46	CSR, KYB	555378	4483053	RM 288.0M; Mid channel island river left; Head of riffle.
10/26/2005	SWW-13	286.3	SR-35, 36 and SBG-1			CSR, KYB, BJB	556958	4481590	Put in at Anderson Boat Ramp; RM 286.3L.
10/26/2005	SWW-14	282.6	SR-80 and SBG-14, 13			CSR, KYB, BJB	562092	4480509	RM 282.6R
10/26/2005	SWW-15	281.8	SR-84 and SBG-12			CSR, KYB, BJB	563192	4479818	
10/26/2005	SWW-16	280.1	SBG-15			CSR, KYB, BJB	565209	4479441	Just downstream of mid-channel island.
10/26/2005	SWW-17	279.1	SBG-16			CSR, KYB, BJB	565929	4478244	
10/23/2005	SW-7	278.5	2005 bulk sample	9:50		CSR, KYB, BRB,	566742	4477299	RM 278.3; Grid over bulk sampling location; heavily vegetated (willows grass etc.) "relict" point bar; downstream end of mid-channel bar; in main arm of river.
10/23/2005	SW-8	275.8	2005 bulk sample			CSR, KYB, BRB,	568443	4473809	
10/22/2005	SW-6	271.8	2005 bulk sample	11:17	11:26	EXL, CSR, KYB	569780	4467772	
10/19/2005	SW-2	239.4	2005 bulk sample	16:00		CSR, REL	572567	4443930	Name: Blackberry riffle; Avoided freeze core and bulk sampling sites (Wolman count taken after samples taken); Grid - 1 pace separation not perfect 10/10 pace grid.
10/20/2005	SW-3	236.8	2005 bulk sample	9:47	10:01	EXL, CSR, KW	573532	4440290	Roughly 10x10 grid (paces) around the bulk sampling location at head of point bar / head of riffle. Water depth = 3-6 inches.
10/20/2005	SW-4	234.2	2005 bulk sample			EXL, CSR, KW	575147	4437499	

2005 Wolman Pebble Count Site Notes

Date	Name	RM	Analog to...	Start Time	End Time	Crew	Northing	Easting	Notes
10/18/2005	SW-1	228.2	2005 bulk sample	12:18	12:30	CSR, MRF, KYB	575757	4429380	RM 228.4; Bulk sample location; MRF: "Did a grid over the location of the permeability and bulk sampling site, for the Wolman counts. ~20 m d/s of LWD snag on RR. Near RR bank. Grid is representative of channel bed material in the site location." Photo nu
10/21/2005	SW-5	211	2005 bulk sample	10:10		EXL, CSR, KW	580367	4411921	
10/24/2005	SW-9	163.2	2005 bulk sample	12:25		EXL, CSR			Name: Princeton; Just downstream of mid-channel island (tip) head of riffle made grid over bulk sampling location 10 pace x 10 pace.
12/14/2005	SW-10	273.5	Scour chain site			KYB., CSR	567961	4469953	

2005 Sacramento River Bulk Sampling Data

combined and normalized

Combined samples (fraction by weight on seive)

	surface									subsurface								
Sieve	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9
12 in	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6 in	0	0	0.0951	0	0	0.1981	0.1605	0.3617	0	0	0	0.0288	0	0	0.0489	0	0	0
3 in	0.1626	0.3469	0.3107	0.0997	0.0335	0.4444	0.2944	0.2731	0.046	0.0942	0.0699	0.1941	0.0073	0.0636	0.2198	0.0525	0.0512	0
1.5 in	0.4729	0.381	0.2699	0.4516	0.552	0.1346	0.3026	0.2252	0.182	0.296	0.2374	0.1917	0.2373	0.2812	0.182	0.3009	0.1743	0.0391
0.75 in	0.2709	0.1202	0.1476	0.1695	0.197	0.086	0.1314	0.0707	0.2762	0.2092	0.1629	0.1358	0.2317	0.1526	0.1331	0.2315	0.2497	0.1566
0.375 in	0.069	0.0839	0.0816	0.1157	0.0985	0.0522	0.0572	0.0385	0.1967	0.1358	0.1351	0.1214	0.1308	0.1409	0.1109	0.1281	0.2102	0.2723
#4	0.0173	0.0274	0.0427	0.0699	0.0447	0.0347	0.0272	0.0175	0.1342	0.0942	0.0793	0.0971	0.0947	0.1028	0.0961	0.0777	0.1235	0.2265
#8	0.0029	0.0081	0.0198	0.0241	0.0155	0.019	0.0111	0.0058	0.0683	0.047	0.0349	0.074	0.0563	0.0499	0.0642	0.0381	0.0553	0.1035
#16	0.0013	0.0088	0.0142	0.0172	0.0131	0.0163	0.0056	0.0025	0.0354	0.0269	0.0513	0.077	0.0454	0.0484	0.0641	0.0244	0.0486	0.0585
#30	0.0013	0.0156	0.0107	0.0226	0.0201	0.0067	0.0032	0.0013	0.0216	0.0252	0.1379	0.054	0.0526	0.067	0.0418	0.0457	0.0276	0.0286
#50	0.0008	0.0058	0.0057	0.0177	0.0196	0.0037	0.0038	0.0021	0.0298	0.0219	0.0749	0.0186	0.0848	0.074	0.0217	0.078	0.0365	0.0513
#100	0.0006	0.0014	0.0015	0.0081	0.0046	0.0029	0.0024	0.0013	0.0056	0.0351	0.0137	0.0053	0.0455	0.0154	0.0125	0.0205	0.0194	0.0523
#200	0.0003	0.0006	0.0004	0.0025	0.0007	0.0009	0.0004	0.0002	0.002	0.012	0.0018	0.0014	0.0093	0.0023	0.0033	0.0022	0.0029	0.0074
Pan	0.0001	0.0004	0.0002	0.0014	0.0006	0.0003	0.0001	7E-05	0.0022	0.0024	0.001	0.0008	0.0044	0.0017	0.0015	0.0004	0.0008	0.0038
Total	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Combined samples (fraction by weight finer than seive)

	surface									subsurface								
Sieve (mm)	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9
304.80	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
152.40	1	1	0.9049	1	1	0.8019	0.8395	0.6383	1	1	1	0.9712	1	1	0.9511	1	1	1
76.20	0.8374	0.6531	0.5942	0.9003	0.9665	0.3575	0.5451	0.3653	0.954	0.9058	0.9301	0.7771	0.9927	0.9364	0.7313	0.9475	0.9488	1
38.10	0.3645	0.2721	0.3243	0.4487	0.4145	0.2229	0.2425	0.1401	0.772	0.6098	0.6927	0.5854	0.7554	0.6552	0.5493	0.6466	0.7745	0.9609
19.05	0.0936	0.1519	0.1767	0.2792	0.2175	0.1369	0.1111	0.0694	0.4958	0.4006	0.5299	0.4496	0.5237	0.5026	0.4162	0.4151	0.5248	0.8043
9.53	0.0246	0.068	0.0951	0.1635	0.119	0.0846	0.0538	0.0309	0.2992	0.2647	0.3947	0.3282	0.393	0.3617	0.3053	0.287	0.3146	0.5319
4.75	0.0073	0.0407	0.0524	0.0936	0.0743	0.0499	0.0266	0.0134	0.165	0.1706	0.3155	0.231	0.2983	0.2588	0.2092	0.2093	0.1911	0.3054
2.38	0.0044	0.0325	0.0326	0.0695	0.0587	0.031	0.0155	0.0076	0.0967	0.1236	0.2806	0.157	0.242	0.2089	0.145	0.1712	0.1358	0.2019
1.19	0.0031	0.0237	0.0184	0.0524	0.0456	0.0146	0.0099	0.005	0.0613	0.0967	0.2293	0.08	0.1966	0.1605	0.0809	0.1468	0.0872	0.1434
0.59	0.0019	0.0081	0.0077	0.0298	0.0255	0.0079	0.0067	0.0038	0.0397	0.0715	0.0914	0.026	0.144	0.0934	0.039	0.1011	0.0596	0.1148
0.30	0.001	0.0023	0.002	0.012	0.0059	0.0041	0.0029	0.0016	0.0099	0.0495	0.0165	0.0074	0.0592	0.0194	0.0173	0.0231	0.0231	0.0635
0.15	0.0004	0.0009	0.0005	0.0039	0.0013	0.0012	0.0005	0.0003	0.0043	0.0144	0.0028	0.0021	0.0137	0.004	0.0048	0.0026	0.0037	0.0112
0.07	0.0001	0.0004	0.0002	0.0014	0.0006	0.0003	0.0001	7E-05	0.0022	0.0024	0.001	0.0008	0.0044	0.0017	0.0015	0.0004	0.0008	0.0038

2005 Sacramento River Bulk Sampling Data

from sheets [raw wet sieve] and [raw dry sieve] of spreadsheet "2005 Sacramento River grain size results.xls"

Wet samples (weight on seive, kg)

	surface									subsurface								
Sieve	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9
12 in	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6 in	0	0	4.9	0	0	44	33.1	80.8	0	0	0	4.8	0	0	7.5	0	0	0
3 in	6.6	15.3	16	5	1.8	98.7	60.7	61	2.2	16.3	13.6	32.3	0.9	9.3	33.7	6.8	5.7	0
1.5 in	19.2	16.8	13.9	22.65	29.7	29.9	62.4	50.3	8.7	51.2	46.2	31.9	29.4	41.1	27.9	39	19.4	4.6
0.75 in	11	5.3	7.6	8.5	10.6	19.1	27.1	15.8	13.2	36.2	31.7	22.6	28.7	22.3	20.4	30	27.8	18.4
0.375 in	2.8	3.7	4.2	5.8	5.3	11.6	11.8	8.6	9.4	23.5	26.3	20.2	16.2	20.6	17	16.6	23.4	32
#4	0.7	1.2	2.2	3.5	2.4	7.7	5.6	3.9	6.4	16.2	15.4	16.1	11.6	15	14.7	10	13.7	26.5
Pan	0.4	2.2	3.3	5.7	5.1	12.9	6.5	3.7	9.3	34.7	72.7	42.4	44.3	43.6	36.4	33	24.8	41.7
Total	*40.7*	*44.5*	*52.1*	*51.15*	*54.9*	*223.9*	*207.2*	*224.1*	*49.2*	*178.1*	*205.9*	*170.3*	*131.1*	*151.9*	*157.6*	*135.4*	*114.8*	*123.2*

Pan subsample (kg)

wet	0.4	2.2	3.3	5.7	5.1	12.9	6.5	3.7	9.3	34.7	17.4	10.9	13.5	11.4	14.4	10.8	11.4	11.7
dry	0.3	1.8	2.7	4.7	4	11.1	5.5	3	7.9	29.6	14.7	9.9	11.3	9.9	12.7	8.9	9.8	10.1
"Dry pan"	*0.3*	*1.8*	*2.7*	*4.7*	*4*	*11.1*	*5.5*	*3*	*7.9*	*29.6*	*61.42*	*38.51*	*37.08*	*37.86*	*32.1*	*27.19*	*21.32*	*36*
"Dry total"	*40.6*	*44.1*	*51.5*	*50.15*	*53.8*	*222.1*	*206.2*	*223.4*	*47.8*	*173*	*194.6*	*166.4*	*123.9*	*146.2*	*153.3*	*129.6*	*111.3*	*117.5*

Dry samples (weight on seive, g)

	surface									subsurface								
Sieve	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9
#4	2.9	3.7	0.4	1.7	1.2	0.7	4	3.1	2	3.1	0.5	2	3.4	0.8	1	3.1	2.9	3.5
#8	148.1	207	429.4	306.4	208.9	414.5	533.3	460.6	496.5	278	138	377.7	186.5	200.1	322	207.3	365.6	375
#16	65.5	224.3	308.7	218.9	176.8	356.7	272.3	201	257.7	159.4	202.7	393.1	150.6	194.1	321.8	132.5	320.9	211.8
#30	64.1	397	231.9	287.7	270	147.1	152.8	101.4	156.9	149.1	545.2	275.4	174.4	268.6	209.9	248.6	182.6	103.6
#50	42.5	146.1	122.6	226.1	263.3	81.2	185.3	167.1	217	129.8	296.1	95.1	281.1	296.4	109.1	424.5	240.9	185.9
#100	32.2	34.6	32.8	103.4	61.8	63.8	113.9	106.2	40.6	207.5	54	26.9	150.8	61.8	62.5	111.4	128.4	189.6
#200	13.5	14.5	7.6	31.6	9.2	19.2	19.2	18.5	14.8	71.3	7.3	6.9	30.8	9.1	16.6	11.9	19	26.9
Pan	6.9	9.5	3.6	18.1	8.5	7.4	5.7	5.7	16.3	14.2	3.8	3.9	14.6	7	7.6	2.4	5.3	13.7
Total	*375.7*	*1037*	*1137*	*1194*	*999.7*	*1091*	*1287*	*1064*	*1202*	*1012*	*1248*	*1181*	*992.2*	*1038*	*1051*	*1142*	*1266*	*1110*

source file: pfb_analysis_2005 grain size distributions

2005 Raw Bulk Sampling Data

	Surface mass in kg								Sub-Surface mass in kg								
size clas:	6-12 in	3-6 in	1.5-3 in	.75-1.5 in	.375-.75 in	#4-3.75	#4-	#4- dry	6-12 in	3-6 in	1.5-3 in	.75-1.5 in	.375-.75 in	#4-3.75	#4-	#4- dry	
SW-1	0	6.6	19.2	11	2.8	0.7	0.4			6.2	14.2	8.9	6	3.9			largest surface particle: 4.5 in
SW-1										3.5	10.3	6.8	4.2	3.1			largest subsurface particle: 3.75 in
SW-1										3.4	8.7	9.1	5.4	3.9			velocity is high; used flow curtain upstream;
SW-1										3.2	11.9	7.2	4.5	3	15.7		#4- 100 lb scale reads 81.0 lbs total… differs from 20 kg scale
SW-1										0	6.1	4.2	3.4	2.3	19	TWO	RM 228.2; river right
Total:	0	6.6	19.2	11	2.8	0.7	0.4	0.3	0	16.3	51.2	36.2	23.5	16.2	34.7	16.2	retained entire 34.7kg of wet subsurface sample #4- for lab anal.
219.1	482.02															13.4	10/18/2005
kg	lbs																Koll Buer, Mike Fainter and Cliff Riebe
SW-2	0	15.3	16.8	5.3	3.7	1.2	2.2		0	10.4	13	17.5	13.7	8.3	19.4		largest surface particle: 4.75 in
SW-2										3.2	12.4	14.2	12.6	7.1	11.8		largest sub-surface particle: 4.5 in
SW-2											5.3				20		RM 239.6; river right; Blackberry riffle
SW-2											15.5				17.5		10/19/2005
SW-2															4		no flow curtain; used sugar scoop
Total:	0	15.3	16.8	5.3	3.7	1.2	2.2	1.8	0	13.6	46.2	31.7	26.3	15.4	72.7	14.7	retained 17.4 kg for of wet subsurface sample for lab analysis
252.2	554.84																Koll Buer and Mike Fainter
kg	lbs																
SW-3	4.9	8.3	13.9	7.6	4.2	2.2	3.3		4.8	14.2	18.9	12.7	11.6	9.4	14.6		largest surface particle: 6.25 in: 4.9 kg
SW-3		7.7								11.2	13	9.9	8.6	6.7	14		largest sub-surface particle: 7.875 in
SW-3										6.9					13.8		RM 236.8; river left
SW-3																	10/20/2005
SW-3																	no flow curtain; used sugar scoop
Total:	4.9	16	13.9	7.6	4.2	2.2	3.3	2.7	4.8	32.3	31.9	22.6	20.2	16.1	42.4	9.9	retained 10.9 kg of wet subsurface fines for lab analysis
225.1	495.22																Koll Buer and Kyle
kg	lbs																
SW-4		5	12.9	8.5	5.8	3.5	5.7			0.9	16.2	15.9	16.2	11.6	16.9		largest surface particle: 3.75 in
SW-4			9.75								13.2	12.8			9.6		largest sub-surface particle: 3.375 in
SW-4															17.8		RM 234.2; river right
SW-4																	10/20/2005
SW-4								TWO									no flow curtain; used sugar scoop
Total:	0	5	22.65	8.5	5.8	3.5	5.7	1.5	0	0.9	29.4	28.7	16.2	11.6	44.3	11.3	retained 13.5 kg of wet subsurface fines for lab analysis
183.75	404.25							3.2									Koll Buer and Cliff Riebe
kg	lbs																
SW-5	0	1.8	10.9	10.6	5.3	2.4	5.1		0	9.3	18.1	15.4	13.4	15	19.1		largest surface particle: 3.5 in
SW-5			18.8								16.1	6.9	7.2		17.5		largest sub-surface particle: 4.5 in
SW-5											6.9				7		RM 211.0; river left
SW-5																	10/21/2005
SW-5																	no flow curtain; used sugar scoop
Total:	0	1.8	29.7	10.6	5.3	2.4	5.1	4	0	9.3	41.1	22.3	20.6	15	43.6	9.9	retained 11.4 kg of wet subsurface fines for lab analysis
210.8	463.76																Koll Buer and Kyle
kg	lbs																
SW-6	12.8	14.7	13.9	8.7	11.6	7.7	12.9		7.5	7.6	15.8	10.6	9.4	8.2	19.8		largest surface particle: 7.75 in
SW-6	16.7	15.4	5	10.4						16.9	12.1	9.8	7.6	6.5	16.6		largest sub-surface particle: 6.75 in
SW-6	5.4	12	11							9.2							RM 271.8; river right
SW-6	9.1	7.8															10/22/2005
SW-6		15.3															no flow curtain; used sugar scoop
		18.6															
		14.9															
Total:	44	98.7	29.9	19.1	11.6	7.7	12.9	11.1	7.5	33.7	27.9	20.4	17	14.7	36.4	12.7	retained 14.4 kg of wet subsurface fines for lab analysis
392.6	863.72																Koll Buer and Kyle
kg	lbs																

2005 Raw Bulk Sampling Data

	Surface mass in kg								Sub-Surface mass in kg								
size clas	6-12 in	3-6 in	1.5-3 in	.75-1.5 in	.375-.75 in	#4-3.75	#4-	#4- dry	6-12 in	3-6 in	1.5-3 in	.75-1.5 in	.375-.75 in	#4-3.75	#4-	#4- dry	
SW-7	11.3	17.8	10	13.7	11.8	5.6	6.5		0	6.8	14	11.4	16.6	10	15.2		largest surface particle: 7.5 in
SW-7	14.2	12.4	17.8	13.4							13.2	18.6			17.8		largest sub-surface particle: 4 in
SW-7	7.6	10	13.6								11.8						RM 278.5; river right
SW-7		14.3	10.2														10/23/2005
SW-7		6.2	10.8														no flow curtain; used sugar scoop
																	retained 10.8 kg of wet subsurface fines for lab analysis
Total:	33.1	60.7	62.4	27.1	11.8	5.6	6.5	5.5	0	6.8	39	30	16.6	10	33	8.9	Koll Buer and Bjorn Buer
348.1	765.82																
kg	lbs																
SW-8	16.2	9.2	13.4	9.2	5.8	3.9	3.7			5.7	9.8	11.2	13.5	8.2	8.9		largest surface particle: 7.75 in
SW-8	11.8	14.2	9.6	6.6	2.8						9.6	5.3	9.9	5.5	15.9		largest sub-surface particle: 4 in
SW-8	11.6	18.2	11.7									11.3					RM 275.8; river right
SW-8	11.4	5.4	15.6														10/23/2005
SW-8	10.6	14															no flow curtain; used sugar scoop
SW-8	19.2																retained 11.4 kg of wet subsurface fines for lab analysis
Total:	80.8	61	50.3	15.8	8.6	3.9	3.7	3	0	5.7	19.4	27.8	23.4	13.7	24.8	9.8	Koll Buer and Bjorn Buer
341.9	752.18																
kg	lbs																
SW-9	0	2.2	8.7	13.2	9.4	6.4	9.3		0	0	4.6	18.4	14.2	10.1	17.4		largest surface particle: 3.75 in
SW-9													17.8	16.4	17.1		largest sub-surface particle: < 3 but > 1.5 in
SW-9															7.2		RM 163.2; river right
SW-9																	10/24/2005
SW-9																	no flow curtain; used sugar scoop
SW-9																	retained 11.7 kg of wet subsurface fines for lab analysis
Total:	0	2.2	8.7	13.2	9.4	6.4	9.3	7.9	0	0	4.6	18.4	32	26.5	41.7	10.1	Cliff Riebe and Evan Lue
180.3	396.66																
kg	lbs																

Source file: 265 00 gravel study field data

Date	Crew 1	Crew 2	RM	Location name	perm site code on data sheet	perm site number	depth below armor (inches)	repetition number	clarity (scale = 0 to 5)	start height (cm)	end height (cm)	time (seconds)	fill rate (cm/sec)	comments/notes includes voltages (V) before and after battery changes
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	6	1						aborted; moved head of sipper
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	6	2	0	0	37.5	66	0.568	water depth: 16.5 inches
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	6	3	0	0	36	68	0.529	photo # 194
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	6	4	0	0	35.7	69	0.517	
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	6	5	0	0	34.9	77	0.453	
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	6	6	0	0	34.8	64	0.544	
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	12	1	1	0	1.1	157	0.007	
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	12	2	1	0	1.1	156	0.007	
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	12	3	1	0	1.6	154	0.010	
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	12	4	0	0	2.2	154	0.014	
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	12	5	0	0	1.4	154	0.009	
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	18	1						aborted; battery died
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	18	2	2	0	1.5	275	0.005	
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	18	3	2	0	1.6	278	0.006	
10/18/2005	Cliff	Mike	228.2	SW-1	a	1	18	4	2	0	1.5	274	0.005	
10/19/2005	Cliff	Russ	239.4	SW-2	freeze core	3	14	1	4	0	27.4	90	0.304	water depth: 16.25 inches
10/19/2005	Cliff	Russ	239.4	SW-2	freeze core	3	14	2	3	0	32.4	95	0.341	
10/19/2005	Cliff	Russ	239.4	SW-2	freeze core	3	14	3	1	0	29.4	90	0.327	
10/19/2005	Cliff	Russ	239.4	SW-2	freeze core	3	14	4	1	0	32.4	95	0.341	
10/19/2005	Cliff	Russ	239.4	SW-2	freeze core	3	14	5	0.5	0	30.2	90	0.336	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	6	1	0	0	16.5	120	0.138	water depth: 15 inches
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	6	2	0	0	16.2	119	0.136	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	6	3	0	0	17.3	119	0.145	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	6	4	0	0	15.9	120	0.133	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	6	5	0	0	13.2	120	0.110	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	12	1	2	0	29.5	120	0.246	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	12	2	1	0	29.4	120	0.245	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	12	3	1	0	29.6	120	0.247	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	12	4	1	0	29.7	120	0.248	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	12	5	0	0	30.1	120	0.251	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	18	1	3	0	4.8	240	0.020	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	18	2	3	0	4.4	240	0.018	
10/19/2005	Cliff	Mike	239.4	SW-2	a	1	18	3	2	0	4.9	240	0.020	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	6	1	2.5	0	7.8	150	0.052	d/s of freeze core on thalweg side
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	6	2	1	0	8.2	150	0.055	water depth: 17.5 inches
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	6	3	0	0	7.9	150	0.053	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	6	4	0	0	9	150	0.060	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	6	5	0	0	6.5	150	0.043	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	12	1	3	0	1.8	270	0.007	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	12	2	3	0	2.3	270	0.009	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	12	3	2	0	2.3	270	0.009	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	12	4	1	0	1.7	270	0.006	battery running low

Date	Crew 1	Crew 2	RM	Location name	perm site code on data sheet	perm site number	depth below armor (inches)	repetition number	clarity (scale = 0 to 5)	start height (cm)	end height (cm)	time (seconds)	fill rate (cm/sec)	comments/notes includes voltages (V) before and after battery changes
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	12							no measurement
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	18	1	4	0	4.8	150	0.032	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	18	2	4	0	5.9	150	0.039	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	18	3	4	0	6.4	155	0.041	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	18	4	3	0	6.2	150	0.041	
10/19/2005	Cliff	Russ	239.4	SW-2	b	2	18	5	3	0	6.2	150	0.041	
10/19/2005	Cliff	Russ	239.4	SW-2	c	3	6	1	2	0	9.2	120	0.077	water depth: 25.5 inches
10/19/2005	Cliff	Russ	239.4	SW-2	c	3	6	2	0.5	0	8.9	120	0.074	
10/19/2005	Cliff	Russ	239.4	SW-2	c	3	6	3	0	0	9.3	120	0.078	
10/19/2005	Cliff	Russ	239.4	SW-2	c	3	6	4	0	0	9.8	120	0.082	
10/19/2005	Cliff	Russ	239.4	SW-2	c	3	6	5	0	0	10.3	120	0.086	
10/19/2005	Cliff	Russ	239.4	SW-2	c	3	12	1						aborted; battery died
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	6	1	0.5	0	25	30	0.833	water depth: 11 inches
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	6	2	0	0	24	30	0.800	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	6	3	0	0	24.3	30	0.810	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	6	4	0	0	24.8	30	0.827	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	6	5	0	0	24.8	30	0.827	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	12	1	4	0	22.8	90	0.253	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	12	2	3	0	23.8	90	0.264	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	12	3	2	0	23.9	90	0.266	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	12	4	2	0	23.8	90	0.264	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	12	5	1	0	23.8	89	0.267	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	18	1	4	0	11.9	150	0.079	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	18	2	4	0	13.5	150	0.090	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	18	3	3	0	13	150	0.087	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	18	4	2	0	13.2	150	0.088	
10/20/2005	Cliff	Evan	236.8	SW-3	a	1	18	5						sipper lock slipped; stopped at 4 eps
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	6	1	2	0	16.2	60	0.270	water depth: 12 inches
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	6	2	1	0	17.3	60	0.288	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	6	3	0.5	0	16.7	60	0.278	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	6	4	0	0	17.8	60	0.297	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	6	5	0	0	16.5	60	0.275	battery at 11.7 V
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	6	6	0	0	13.5	60	0.225	changed battery; new battery at 12.5 V
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	6	7	0	0	13.7	60	0.228	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	12	1	4	0	14.7	150	0.098	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	12	2	3	0	15.1	150	0.101	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	12	3	2	0	14.9	150	0.099	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	12	4	1.5	0	15.7	150	0.105	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	12	5	1	0	14.1	150	0.094	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	18	1	5	0	18.6	120	0.155	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	18	2	4	0	18.4	120	0.153	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	18	3	3.5	0	18.2	120	0.152	

Date	Crew 1	Crew 2	RM	Location name	perm site code on data sheet	perm site number	depth below armor (inches)	repetition number	clarity (scale = 0 to 5)	start height (cm)	end height (cm)	time (seconds)	fill rate (cm/sec)	comments/notes includes voltages (V) before and after battery changes
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	18	4	2	0	18.8	120	0.157	
10/20/2005	Cliff	Evan	236.8	SW-3	b	2	18	5	1.5	0	18.5	120	0.154	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	6	1	2	0	21.2	60	0.353	water depth: 16 inches
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	6	2	2	0	22.7	60	0.378	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	6	3	2	0	22.2	60	0.370	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	6	4	1	0	22.4	60	0.373	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	6	5	1	0	23.1	60	0.385	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	12	1	1	0	21.6	60	0.360	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	12	2	1	0	21.7	60	0.362	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	12	3	1	0	22	60	0.367	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	12	4	0.5	0	21.1	60	0.352	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	12	5	0.5	0	20.4	60	0.340	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	18	1	4.5	0	17.3	150	0.115	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	18	2	3	0	19.5	150	0.130	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	18	3	2	0	21	150	0.140	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	18	4	1	0	24.3	150	0.162	
10/20/2005	Kyle	Evan	234.2	SW-4	a	1	18	5	0.5	0	25.1	150	0.167	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	6	1	3	0	30	30	1.000	water depth: 15 inches
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	6	2	2	0	32.2	30	1.073	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	6	3	1.5	0	30.6	30	1.020	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	6	4	2	0	31.2	30	1.040	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	6	5	1	0	31.1	30	1.037	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	12	1	3	0	27	30	0.900	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	12	2	2	0	28.2	30	0.940	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	12	3	1	0	27	30	0.900	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	12	4	1	0	27.9	30	0.930	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	12	5	1	0	27.1	30	0.903	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	18	1	5	0	29.5	60	0.492	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	18	2	4	0	34.4	60	0.573	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	18	3	3	0	17.1	30	0.570	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	18	4	3	0	17	30	0.567	
10/20/2005	Kyle	Evan	234.2	SW-4	b	2	18	5	2	0	18.3	30	0.610	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	6	1	2	0	26.3	60	0.438	water depth: 16 inches
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	6	2						trial aborted due to a mistake
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	6	3	1	0	33.2	63	0.527	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	6	4	0	0	34.8	60	0.580	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	6	5	0	0	33.2	60	0.553	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	6	6	0	0	33.4	60	0.557	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	12	1	3	0	24.7	60	0.412	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	12	2	2.5	0	25.3	60	0.422	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	12	3	2	0	26.7	60	0.445	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	12	4	1	0	25.6	60	0.427	

Date	Crew 1	Crew 2	RM	Location name	perm site code on data sheet	perm site number	depth below armor (inches)	repetition number	clarity (scale = 0 to 5)	start height (cm)	end height (cm)	time (seconds)	fill rate (cm/sec)	comments/notes includes voltages (V) before and after battery changes
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	12	5	0.5	0	26.9	60	0.448	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	18	1	4	0	19.4	130	0.149	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	18	2	3	0	19.9	130	0.153	battery: 10.7 V
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	18	3	2	0	22.3	130	0.172	changed battery: 12.7 V
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	18	4	1	0	21.7	130	0.167	
10/20/2005	Cliff	Evan	234.2	SW-4	c	3	18	5	0.5	0	22.7	130	0.175	
10/21/2005	Cliff	Evan	211	SW-5	a	1	6	1	1.5	0	12.4	150	0.083	before raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	6	2	0	0	12.2	150	0.081	before raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	6	3	0	0	12.1	150	0.081	before raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	6	4	0	0	12.3	150	0.082	before raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	6	5	0	0	11.1	150	0.074	before raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	12	1	5	0	0.5	390	0.001	before raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	12	2	4	0	0.8	420	0.002	before raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	12	3	4	0	1.1	420	0.003	before raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	12	4						skipped
10/21/2005	Cliff	Evan	211	SW-5	a	1	12	5						skipped
10/21/2005	Cliff	Evan	211	SW-5	a	1	6	1	0	0	31.1	25	1.244	after raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	6	2	0	0	30.7	25	1.228	after raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	6	3	0	0	31.3	25	1.252	after raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	6	4	0	0	31.8	25	1.272	after raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	6	5	0	0	31.1	25	1.244	after raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	12	1	2	0	13.5	30	0.450	after raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	12	2	0	0	13.3	30	0.443	after raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	12	3	0	0	13.4	30	0.447	after raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	12	4	0	0	13.3	30	0.443	after raking
10/21/2005	Cliff	Evan	211	SW-5	a	1	12	5	0	0	15.3	30	0.510	after raking
10/21/2005	Cliff	Evan	211	SW-5	b	2	6	1	1	0	11.9	60	0.198	
10/21/2005	Cliff	Evan	211	SW-5	b	2	6	2	0	0	12.4	60	0.207	
10/21/2005	Cliff	Evan	211	SW-5	b	2	6	3	0	0	12.3	60	0.205	
10/21/2005	Cliff	Evan	211	SW-5	b	2	6	4	0	0	12.2	60	0.203	
10/21/2005	Cliff	Evan	211	SW-5	b	2	6	5	0	0	12.2	60	0.203	
10/21/2005	Cliff	Evan	211	SW-5	b	2	12	1	5	0	4.7	180	0.026	
10/21/2005	Cliff	Evan	211	SW-5	b	2	12	2	4	0	7	180	0.039	
10/21/2005	Cliff	Evan	211	SW-5	b	2	12	3	3	0	9.4	180	0.052	
10/21/2005	Cliff	Evan	211	SW-5	b	2	12	4	2	0	5.9	180	0.033	
10/21/2005	Cliff	Evan	211	SW-5	b	2	12	5	1	0	8.4	180	0.047	
10/21/2005	Cliff	Evan	211	SW-5	b	2	18	1	5	0	1.6	420	0.004	
10/21/2005	Cliff	Evan	211	SW-5	b	2	18	2	4	0	2.3	300	0.008	
10/21/2005	Cliff	Evan	211	SW-5	b	2	18	3	3	0	2.5	300	0.008	
10/21/2005	Cliff	Evan	211	SW-5	b	2	18	4	2	0	2.3	420	0.005	
10/21/2005	Cliff	Evan	211	SW-5	b	2	18	5	2	0	2.5	420	0.006	
10/22/2005	Cliff	Evan	271.8	SW-6	freeze core	3	14	1	4.5	0	11.8	150	0.079	

Date	Crew 1	Crew 2	RM	Location name	perm site code on data sheet	perm site number	depth below armor (inches)	repetition number	clarity (scale = 0 to 5)	start height (cm)	end height (cm)	time (seconds)	fill rate (cm/sec)	comments/notes includes voltages (V) before and after battery changes
10/22/2005	Cliff	Evan	271.8	SW-6	freeze core	3	14	2	4	0	11.2	150	0.075	
10/22/2005	Cliff	Evan	271.8	SW-6	freeze core	3	14	3	2	0	10.5	150	0.070	
10/22/2005	Cliff	Evan	271.8	SW-6	freeze core	3	14	4	1	0	10.5	150	0.070	
10/22/2005	Cliff	Evan	271.8	SW-6	freeze core	3	14	5	0.5	0	11.1	150	0.074	
10/22/2005	Cliff	Evan	271.8	SW-6	a	1	6	1	0	0	27.6	45	0.613	
10/22/2005	Cliff	Evan	271.8	SW-6	a	1	6	2	0	0	27.2	45	0.604	
10/22/2005	Cliff	Evan	271.8	SW-6	a	1	6	3	0	0	26.4	45	0.587	
10/22/2005	Cliff	Evan	271.8	SW-6	a	1	6	4	0	0	25.9	45	0.576	
10/22/2005	Cliff	Evan	271.8	SW-6	a	1	6	5	0	0	25.5	45	0.567	
10/22/2005	Cliff	Evan	271.8	SW-6	a	1	12	1	0	0	4.8	120	0.040	
10/22/2005	Cliff	Evan	271.8	SW-6	a	1	12	2	0	0	5.1	125	0.041	
10/22/2005	Cliff	Evan	271.8	SW-6	a	1	12	3	0	0	8.3	120	0.069	
10/22/2005	Cliff	Evan	271.8	SW-6	a	1	12	4	0	0	7.5	120	0.063	
10/22/2005	Cliff	Evan	271.8	SW-6	a	1	12	5	0	0	8.9	120	0.074	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	6	1	4	0	4.3	120	0.036	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	6	2	3	0	2.9	120	0.024	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	6	3	2	0	4	120	0.033	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	6	4						skipped
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	6	5	0	0	2.2	120	0.018	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	6	6	0	0	3.7	120	0.031	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	12	1	4	0	3.3	240	0.014	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	12	2	4	0	8	240	0.033	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	12	3	3	0	10.1	240	0.042	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	12	4	3	0	5.8	240	0.024	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	12	5						skipped
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	18	1	5	0	7.4	120	0.062	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	18	2	5	0	7.8	120	0.065	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	18	3	4	0	8.7	120	0.073	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	18	4	3	0	8	120	0.067	
10/22/2005	Cliff	Evan	271.8	SW-6	b	2	18	5	3	0	8.8	120	0.073	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	6	1	3	0	12.3	60	0.205	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	6	2	1	0	10.7	60	0.178	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	6	3	0	0	10.3	60	0.172	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	6	4	0	0	10.7	60	0.178	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	6	5	0	0	11.7	60	0.195	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	12	1	5	0	7.5	135	0.056	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	12	2	5	0	9.8	140	0.070	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	12	3	4	0	8.7	135	0.064	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	12	4	3	0	9.4	135	0.070	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	12	5	3	0	9.7	135	0.072	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	18	1	5	0	2.2	210	0.010	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	18	2						skipped

Date	Crew 1	Crew 2	RM	Location name	perm site code on data sheet	perm site number	depth below armor (inches)	repetition number	clarity (scale = 0 to 5)	start height (cm)	end height (cm)	time (seconds)	fill rate (cm/sec)	comments/notes includes voltages (V) before and after battery changes
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	18	3	5	0	1.8	210	0.009	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	18	4	5	0	2.3	210	0.011	
10/23/2005	Cliff	Kyle	278.5	SW-7	a	1	18	5						skipped
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	6	1	3	0	14.7	60	0.245	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	6	2	0	0	12.8	60	0.213	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	6	3	0	0	16.6	65	0.255	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	6	4	0	0	15.2	60	0.253	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	6	5	0	0	13.4	60	0.223	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	12	1	5	0	4.4	150	0.029	slightly less than 12 inches depth
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	12	2	4	0	5.2	158	0.033	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	12	3	2	0	5.2	158	0.033	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	12	4	2	0	5.9	155	0.038	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	12	5	2	0	8.7	155	0.056	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	18	1	5	0	5.2	120	0.043	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	18	2	5	0	6	120	0.050	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	18	3	4	0	5.4	120	0.045	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	18	4	3	0	4.6	120	0.038	
10/23/2005	Cliff	Kyle	278.5	SW-7	b	2	18	5	2	0	4.4	120	0.037	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	6	1	4	0	11.3	60	0.188	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	6	2	3	0	12.1	60	0.202	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	6	3	2	0	11.2	60	0.187	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	6	4	2	0	12.5	60	0.208	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	6	5	1	0	12.2	60	0.203	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	12	1	5	0	23	45	0.511	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	12	2	3	0	23.9	45	0.531	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	12	3	2	0	25.1	45	0.558	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	12	4	2	0	25.3	45	0.562	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	12	5	1	0	25.2	45	0.560	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	18	1	5	0	21.2	60	0.353	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	18	2	3	0	23.1	60	0.385	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	18	3	3	0	24.2	60	0.403	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	18	4	2	0	26.5	60	0.442	
10/23/2005	Cliff	Kyle	275.8	SW-8	a	1	18	5	1	0	26.2	60	0.437	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	6	1	4	0	3.7	150	0.025	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	6	2	3	0	4.3	150	0.029	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	6	3	1	0	3.5	150	0.023	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	6	4	0	0	4.5	150	0.030	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	6	5	0	0	3.7	150	0.025	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	12	1	5	0	4.7	120	0.039	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	12	2	4	0	5.1	120	0.043	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	12	3	4	0	5.3	120	0.044	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	12	4	3	0	5.4	120	0.045	

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10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	12	5	2	0	5.3	120	0.044	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	18	1	5	0	2	180	0.011	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	18	2	5	0	1.9	180	0.011	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	18	3	4	0	2.7	180	0.015	
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	18	4						
10/23/2005	Cliff	Kyle	275.8	SW-8	b	2	18	5						
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	6	1	3	0	22.5	60	0.375	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	6	2	2	0	24.2	65	0.372	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	6	3	1	0	24.2	60	0.403	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	6	4	0.5	0	24.7	60	0.412	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	6	5	0.5	0	23.2	60	0.387	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	12	1	4	0	7.6	95	0.080	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	12	2	3	0	7.8	95	0.082	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	12	3	2	0	8.4	95	0.088	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	12	4	1	0	7.9	95	0.083	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	12	5	1	0	9.4	95	0.099	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	17.5	1	5	0	10.8	95	0.114	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	17.5	2	3	0	15.2	95	0.160	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	17.5	3	2	0	8.7	60	0.145	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	17.5	4	1	0	16.3	95	0.172	
10/24/2005	Cliff	Evan	163.2	SW-9	a	1	17.5	5	0	0	18.5	95	0.195	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	6	1	3	0	18.3	60	0.305	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	6	2	2	0	18.8	60	0.313	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	6	3	1	0	19.6	60	0.327	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	6	4	0	0	19.2	60	0.320	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	6	5	0	0	18.8	60	0.313	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	12	1	4	0	13.4	60	0.223	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	12	2	2	0	17.8	65	0.274	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	12	3	1	0	17.4	60	0.290	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	12	4	1	0	18.7	60	0.312	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	12	5	1	0	18	60	0.300	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	18	1	4	0	9	90	0.100	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	18	2	3	0	9.4	90	0.104	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	18	3	2	0	9.6	90	0.107	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	18	4	1	0	10.4	90	0.116	
10/24/2005	Cliff	Evan	163.2	SW-9	b	2	18	5	1	0	4.8	60	0.080	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	6	1						
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	6	2	3	0	6.7	70	0.096	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	6	3	2	0	6.6	70	0.094	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	6	4	1	0	7.5	70	0.107	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	6	5	0	0	7.4	70	0.106	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	6	6	0	0	7.4	70	0.106	

Date	Crew 1	Crew 2	RM	Location name	perm site code on data sheet	perm site number	depth below armor (inches)	repetition number	clarity (scale = 0 to 5)	start height (cm)	end height (cm)	time (seconds)	fill rate (cm/sec)	comments/notes includes voltages (V) before and after battery changes
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	12	1	4	0	4.7	90	0.052	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	12	2	3	0	4.5	90	0.050	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	12	3	2	0	4.7	90	0.052	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	12	4	1.5	0	4.8	90	0.053	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	12	5	1	0	6.1	100	0.061	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	18	1	5	0	5.7	120	0.048	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	18	2	4	0	7	120	0.058	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	18	3	3	0	7.3	120	0.061	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	18	4	2	0	7.6	120	0.063	
10/24/2005	Cliff	Evan	163.2	SW-9	c	3	18	5	1	0	7.5	120	0.063	
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	6	1	1	0	23.3	60	0.388	before raking (large subsurface particles)
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	6	2	0	0	26.9	60	0.448	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	6	3	0	0	26.4	60	0.440	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	6	4	0	0	27.6	60	0.460	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	6	5	0	0	25.6	60	0.427	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	12	1	4	0	5.6	90	0.062	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	12	2	3	0	7.8	95	0.082	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	12	3	2	0	5.6	90	0.062	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	12	4	1	0	5.5	90	0.061	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	12	5	0	0	5.4	90	0.060	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	6	1	1	0	22	50	0.440	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	6	2	0	0	24.3	50	0.486	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	6	3	0	0	21.1	50	0.422	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	6	4	0	0	27.1	60	0.452	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	6	5	0	0	25.4	60	0.423	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	12	1	3	0	3.3	100	0.033	after raking (large subsurface particles)
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	12	2	3	0	4.2	100	0.042	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	12	3	4	0	4.3	100	0.043	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	12	4	1	0	5.2	100	0.052	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	c	3	12	5	0	0	5.4	100	0.054	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	6	1	0	0	22.3	45	0.496	before raking (2 m to bank side of SW-7c)
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	6	2	0	0	23.9	45	0.531	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	6	3	0	0	23.6	45	0.524	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	6	4	0	0	21.5	45	0.478	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	6	5	0	0	22.9	45	0.509	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	12	1	3	0	8.2	90	0.091	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	12	2	2	0	8.5	90	0.094	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	12	3	1	0	8.9	90	0.099	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	12	4	0	0	8.3	90	0.092	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	12	5	0	0	7.8	90	0.087	before raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	6	1	0	0	26.8	25	1.072	after raking (close to the max pumping rate)
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	6	2	0	0	26.8	25	1.072	after raking

Date	Crew 1	Crew 2	RM	Location name	perm site code on data sheet	perm site number	depth below armor (inches)	repetition number	clarity (scale = 0 to 5)	start height (cm)	end height (cm)	time (seconds)	fill rate (cm/sec)	comments/notes includes voltages (V) before and after battery changes
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	6	3	0	0	25.7	25	1.028	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	6	4	0	0	25.1	25	1.004	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	6	5	0	0	25.8	25	1.032	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	12	1	0	0	8.3	90	0.092	after raking (large subsurface particles)
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	12	2	0	0	9.9	90	0.110	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	12	3	0	0	6.9	90	0.077	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	12	4	0	0	7.5	90	0.083	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	d	4	12	5	0	0	5.9	90	0.066	after raking
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	6	1	1	0	15.3	50	0.306	2 m downstream from bulk sample;
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	6	2	0	0	12.9	50	0.258	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	6	3	0	0	12.5	50	0.250	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	6	4	0	0	11.6	50	0.232	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	6	5	0	0	11.2	50	0.224	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	12	1	2	0	3.3	100	0.033	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	12	2	1	0	4.5	100	0.045	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	12	3	0	0	4	100	0.040	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	12	4	0	0	3.5	100	0.035	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	12	5	0	0	3.5	100	0.035	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	18	1	5	0	4.8	90	0.053	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	18	2	4	0	3.8	90	0.042	V= 11.2
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	18	3	3	0	3.8	90	0.042	V= 12.9 (battery changed)
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	18	4	2	0	4	90	0.044	
10/26/2005	Cliff	Koll	278.5	SW-7	e	5	18	5	1	0	4.2	90	0.047	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 a	2	6	1	2.5	0	11.6	90	0.129	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 a	2	6	2	0	0	11.2	90	0.124	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 a	2	6	3	0	0	12.1	90	0.134	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 a	2	6	4	0	0	12.5	90	0.139	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 a	2	6	5	0	0	11.8	90	0.131	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 a	2	12	1	1	0	5.5	120	0.046	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 a	2	12	2	1	0	5.6	120	0.047	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 a	2	12	3	0	0	5.6	120	0.047	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 a	2	18	1	1	0	4.5	181	0.025	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 a	2	18	2	1	0	7.2	240	0.030	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 b	3	6	1	0	0	7.5	75	0.100	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 b	3	6	2	0	0	5.6	75	0.075	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 b	3	6	3	0	0	5.2	75	0.069	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 b	3	6	4	0	0	5.2	75	0.069	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 b	3	6	5	0	0	4.7	75	0.063	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 b	3	12	1	1	0	5.1	120	0.043	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 b	3	12	2	0	0	3.8	120	0.032	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 b	3	12	3	0	0	4.1	120	0.034	
10/26/2006	Cliff	Koll	228.2	SW-1	2006 b	3	18	1	2	0	7.2	180	0.040	

Date	Crew 1	Crew 2	RM	Location name	perm site code on data sheet	perm site number	depth below armor (inches)	repetition number	clarity (scale = 0 to 5)	start height (cm)	end height (cm)	time (seconds)	fill rate (cm/sec)	comments/notes includes voltages (V) before and after battery changes
10/26/2006	Cliff	Koll	228.2	SW-1	2006 b	3	18	2	2	0	7.8	180	0.043	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	6	1	1	0	14.5	60	0.242	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	6	2	0	0	14.5	60	0.242	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	6	3	0	0	14.8	60	0.247	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	6	4	0	0	14.3	60	0.238	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	6	5	0	0	14.2	60	0.237	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	12	1	4	0	3.2	150	0.021	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	12	2	4	0	3.1	150	0.021	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	12	3	3	0	4.4	150	0.029	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	18	1	4	0	4.2	120	0.035	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	18	2	4	0	4.2	120	0.035	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 a	5	18	3	4	0	4.6	120	0.038	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 b	6	6	1	3	0	4.6	120	0.038	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 b	6	6	2	2	0	5.1	120	0.043	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 b	6	6	3	1	0	4.7	120	0.039	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 b	6	12	1	2.5	0	3.8	300	0.013	
10/26/2006	Cliff	Koll	239.4	SW-2	2006 b	6	18	1	3	0	0.7	300	0.002	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	6	1	4	0	4.9	60	0.082	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	6	2	3	0	5.7	60	0.095	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	6	3	3	0	5.8	60	0.097	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	6	4	2	0	5.6	60	0.093	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	6	5	2	0	5.8	60	0.097	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	12	1	5	0	4.6	150	0.031	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	12	2	4	0	5.2	150	0.035	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	12	3						aborted
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	12	4	2	0	5.7	150	0.038	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	18	1	5	0	3.2	180	0.018	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	18	2	5	0	5.1	180	0.028	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 a	4	18	3	4	0	6.2	180	0.034	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	6	1	5	0	4.2	90	0.047	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	6	2	4		5.1	90	0.057	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	6	3	3	0	4.9	90	0.054	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	6	4	2	0	5.8	90	0.064	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	12	1	5	0	5.3	105	0.050	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	12	2	5	0	5.9	105	0.056	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	12	3	4	0	6.8	105	0.065	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	12	4	3	0	7.2	105	0.069	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	18	1						aborted
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	18	2						aborted
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	18	3	4	0	4.8	105	0.046	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	18	4	3	0	4.7	105	0.045	
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	18	5	2	0	5.5	105	0.052	

Date	Crew 1	Crew 2	RM	Location name	perm site code on data sheet	perm site number	depth below armor (inches)	repetition number	clarity (scale = 0 to 5)	start height (cm)	end height (cm)	time (seconds)	fill rate (cm/sec)	comments/notes includes voltages (V) before and after battery changes			
10/27/2006	Cliff	Koll	271.8	SW-6	2006 b	5	18	6	2	0	6.2	105	0.059				
Source file: 265 00 gravel study field data																	

General Site Notes

General Notes				
	used 3 ft culvert to isolate bulk samples; Wolman counts by grids; perm samples at multiple depths (typically 6, 12 and 18 inches)			
	used narrow stadpipe for most perm measurements (except those taken at freeze core site)`			
Site Specific Notes				
SW-1	RM 228.2; access from Mill Creek boat ramp; river right; nearly exact same site as 1984 sample BS-8			
	downstream of long outside bank of rip-rap			
	10/18/2005; crew: Mike Fainter, Koll Buer and Cliff Riebe did Wolman Count first; then sampled bulk sample (481 lbs) using CDWR 3 ft culvert; measured permeabilities at one core (3 depths)			
	575757	northing	utm grid:	10
	4429380	easting	datum	wgs 84
	20 m downstream of snag			
	12/16/2005; crew: Cliff Riebe and Koll Buer			
	installed 4 scour chains, 5 m apart in at corners of a grid			
	575743	northing	utm grid:	10
	4429387	easting	datum	wgs 84
	painted 3 plots, 5 ft by 5 ft, 20 m apart, starting (coordinates of central plot)			
	575822	northing	utm grid:	10
	4429341	easting	datum	wgs 84
SW-2	RM 239.6; called this "Blackberry Riffle" but may not be actual Blackberry Riffle; access from lower Red Bluff boat ramp; river right			
	10/19/2005; crew: Mike Fainter, Koll Buer and Cliff Riebe, with Russ Liebig joining at approx. 11 am to help with freeze core and permeability samples			
	started with bulk sample (550 lbs); did freeze core upstream (3 m) of bulk sample; did permeability measurement before freeze core (at just one depth = 14 inches); did 3 perm measurements (2 with 3 different depths and 1 with 1 depth)			
	freeze core was very small; stratified it into surface and subsurface samples			
	572567	northing	utm grid:	10
	4443930	easting	datum	wgs 84
	12/15/2005; crew: Cliff Riebe and Koll Buer			
	installed 4 scour chains, 5 m apart in at corners of a grid			
	572565	northing	utm grid:	10
	443928	easting	datum	wgs 84
	painted 3 plots, 5 ft by 5 ft, 20 m apart, starting at head of riffle and extending downstream			

General Site Notes

SW-3	RM 236.8; access from lower Red Bluff boat ramp; river left					
	10/20/2005; crew: Cliff Riebe, Evan Lue, Koll Buer and Kyle Westfall					
	did Wolman Count; bulk sample (490 lbs); 2 perm measurements with 3 depths each					
	573532	northing	utm grid:	10		
	4440290	easting	datum	wgs 84		
	left reset marks for relocation of bulk sampling site					
	12/15/2005; crew: Cliff Riebe and Koll Buer					
	installed 4 scour chains, 5 m apart in at corners of a grid					
		northing	utm grid:	10		
		easting	datum	wgs 84		
	painted 3 plots, 5 ft by 5 ft, 20 m apart, starting at head of riffle and extending downstream					
	573507	northing	utm grid:	10		
	4440255	easting	datum	wgs 84		
SW-4	RM-234.2; access from lower Red Bluff boat ramp river right					
	10/20/2005; crew: Cliff Riebe, Evan Lue, Koll Buer and Kyle Westfall					
	did Wolman Count; bulk sample (400 lbs); 3 perm measurements with 3 depths each					
	575147	northing	utm grid:	10		
	4437499	easting	datum	wgs 84		
	high (6 m) steep bank here; lots of pockets of sand very close to surface… is this sand here from a local source or is it typical of the river's depositional load here?					
SW-5	RM-211; access from Woodson Bridge launch site; river left					
	10/21/2005; crew: Cliff Riebe, Evan Lue, Koll Buer and Kyle Westfall					
	did Wolman Count; bulk sample (455 lbs); 1 perm measurement with 3 depths plus 1 before and after redd building (2 depths each)					
	580367	northing	utm grid:	10		
	4411921	easting	datum	wgs 84		
	head of riffle; head of bar; side channel to left at this flow (7000 cfs)					
	gradually sloping point bar					

General Site Notes

SW-6	RM-271.8; access from Balls Ferry launch site; river right				
	10/22/2005; crew: Cliff Riebe, Evan Lue, Koll Buer and Kyle Westfall				
	did Wolman Count; bulk sample (840 lbs); freeze core; 2 perm measurements with 2 depths and 3 depths respectively (hit refusal on third depth for one)				
	569780	northing	utm grid:	10	
	4467772	easting	datum	wgs 84	
	head of riffle; head of bar;				
	12/14/2005; crew: Cliff Riebe and Koll Buer				
	failed in effort to install chains				
	painted 3 plots, 5 ft by 5 ft, 20 m apart, starting at head of riffle and extending downstream				
	569767	northing	utm grid:	10	head coordinates
	4467786	easting	datum	wgs 84	
	569782	northing			middle coordinates
	4467773	easting			
	569796	northing			lower coordinates
	4467760	easting			
SW-7	RM-278.5; access from Balls Ferry; river right				
	10/23/2005; crew: Cliff Riebe, Koll Buer; Bjorn Buer; Kyle Westfall				
	did Wolman count; bulk sample (753 lbs); 2 perm measurements with 3 depths each				
	no GPS measurement here				
	very coarse here; looks like relict bar; lots of tall vegetation on bar; location has not changed much according to Koll; perm pipe difficult to drive				
	10/26/2005; crew: Cliff Riebe, Koll Buer; Bjorn Buer				
	got 3 more perm measurements: 1 with 3 depths and 2 with 2 depths each, before and after redd building experiments				
	got GPS measurement this time:				
	566742	northing	utm grid:	10	
	4477299	easting	datum	wgs 84	

General Site Notes

SW-8	RM-275.8; access from Balls Ferry; river right			
	10/23/2005; crew: Cliff Riebe, Koll Buer; Bjorn Buer; Kyle Westfall			
	did Wolman count; bulk sample (746 lbs); 2 perm measurements with 3 depths each			
	568443	northing	utm grid:	10
	4473809	easting	datum	wgs 84
	perm pipe difficult to drive; compacted (?)			
SW-9	RM-163.2; access from Princeton levee road; river right			
	10/24/2005; crew: Cliff Riebe and Evan Lue			
	did Wolman count; bulk sample (379 lbs); 3 perm measurements with three depths each			
	no GPS measurement here			
	perm pipe is easy to drive; very loose gravel			
SW-10	RM-273; access from Balls Ferry; river left			
	12/14/2005; crew: Cliff Riebe and Koll Buer			
	did Wolman count; installed 3 scour chains, 5 m apart in transect running perpendicular to channel			
	567961	northing	utm grid:	10
	4469953	easting	datum	wgs 84
	painted 3 plots, 5 ft by 5 ft, 20 m apart, starting at head of riffle and extending downstream			
SW-11	RM-246.2; access by car along road behind shopping mall (Food Maxxx etc.), river left			
	12/16/2005; crew: Cliff Riebe and Koll Buer			
	installed 4 scour chains, 5 m apart in at corners of a grid			
	565707	northing	utm grid:	10
	4448866	easting	datum	wgs 84
	no paint plots due to public access			
Source file: 265 00 gravel study field data				

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APPENDIX C

GRAVEL STUDY PLAN

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Gravel Study Plan (Appendix C of the Gravel Study Report)

1 PURPOSE

This document describes an investigation of the gravel characteristics and dynamics in the mainstem Sacramento River between Keswick Dam (RM 302) and Colusa (RM 143). This gravel study addresses two project tasks defined in the Scope of Work (SOW) for the Agreement between The Nature Conservancy (TNC) and Stillwater Sciences. The first task (2.1) focuses on refining the flows required to mobilize, scour, and route gravel in the mainstem Sacramento River; the second task (2.3) focuses on characterizing gravel quality and its habitat value in the mainstem Sacramento River. This gravel study includes analysis of existing data, new field studies, and the application of a new sediment transport model.

Studying the distribution, composition and dynamics of gravel in rivers is important because they are key regulators of the extent and quality of aquatic habitats. For example, the grain size distribution and percentage of fine material stored in the subsurface of a channel bed influences the quality of spawning habitat for salmonids. Gravel dynamics also affect salmonid rearing habitat by influencing point bar formation and the downstream eddies associated with them. The frequency of bed mobilization also influences the composition and abundance of aquatic macroinvertebrates, which in turn affects the availability of food for juvenile salmonids. Understanding gravel characteristics and dynamics in the Sacramento River is essential for conserving and restoring its diverse array of habitats and species. However, a recent analysis of flow and ecological processes in the Sacramento River (Kondolf et al. 1999) indicates that current estimates of the flow characteristics (e.g., magnitude, timing, duration) that drive fundamental riverine processes (e.g., bed mobilization and scour, riparian recruitment, bank erosion) are provisional because of limitations and gaps in existing data and models.

2 BACKGROUND

This gravel study plan is part of a larger project initiated by TNC to define ecological flow needs for the mainstem Sacramento River between Keswick Dam (RM 302) and Colusa (RM 143). The general goal of the project is to define flow characteristics (e.g., magnitude, timing, duration, frequency) and associated management actions (e.g., gravel augmentation, changes in bank protection) that influence the creation and maintenance of habitats and habitat conditions for several native species that occur in the Sacramento River corridor. The overall project includes:

- a State of the System (SOS) Report,
- a Decision Analysis (DA) Tool,
- several field studies, and
- the application of numerical models.

The SOS Report synthesizes much of the available information about ecosystem processes, habitats, and selected biota in the Sacramento River corridor, and it presents conceptual models about flow-habitat-biotic linkages to help guide inquiry. The DA Tool is designed to help resource managers and stakeholders evaluate ecological trade-offs associated with different combinations of management actions, such as changes in the flow regime, sediment supply, or bank conditions. The field investigations and modeling applications are designed to address uncertainties, fill data gaps, and test hypotheses about flow-habitat linkages in the mainstem Sacramento River. This study plan describes one of those investigations—the gravel study. The other studies address off-channel habitats, meander migration, and the effects of bank protection on aquatic habitats.

The project components are inter-related. For example, many of the field investigations and modeling applications are designed to test hypotheses that have been developed in the SOS Report. The SOS Report also defines functional relationships among ecological processes, habitats, and focal species that are being used to help structure the DA Tool. The DA Tool will also incorporate the results of the field and modeling studies.

The project is scheduled to be completed by September, 2007, at which time a final report will summarize the results of the different project components.

3 CONCEPTUAL MODEL

In this section, we sketch a conceptual model of gravel dynamics in the mainstem Sacramento River between Keswick Dam (RM 302) and Colusa (RM 143) to lay a foundation for the hypotheses that drive several of the gravel study components. This conceptual model is derived from the SOS Report (Stillwater Sciences 2006), which contains a more extensive discussion of gravel dynamics and its effects on habitats and species in the study reach. Gravel dynamics in the Sacramento River can affect aquatic habitats that support numerous species, but this conceptual model focuses on habitat and habitat conditions that are relevant to anadromous salmonids because these species provide the tightest process-habitat-biotic linkages related to gravel supply and routing.

The study reach encompasses the gravel-bedded reach of the mainstem Sacramento River between Keswick Dam (RM 302) and Colusa (RM 143), which currently supports spawning populations of fall-run, late-fall-run, and winter-run Chinook salmon (*Oncorhynchus tshawytscha)*, in addition to steelhead (*Oncorhynchus mykiss*). The mainstem Sacramento River once supported a spawning population of spring-run Chinook salmon, but it is unclear if a self-sustaining population still spawns in the mainstem channel. These spawning populations require clean gravel for spawning, and the amount and caliber of gravel stored in the Sacramento River channel bed affects the extent, distribution, and quality of salmonid spawning habitat.

3.1 Bed mobilization and scour

High flow events can mobilize and scour gravel stored in the channel bed, routing the sediment downstream. In the alluvial reaches of unregulated rivers, the sediment that is scoured from a local reach is generally replaced by sediment that is transported from upstream, supplied from tributaries, or recruited from storage in river banks. There may be short-term or local changes in the amount of gravel stored in a channel bed because of episodic sediment delivery (e.g., mass wasting events in the watershed) or extreme flow events, but over a broader time span, unregulated rivers generally achieve a balance between sediment supply and routing so that in-channel sediment storage is maintained.

In the Sacramento River, the construction and operation of Shasta and Keswick dams has altered the flow regime and sediment supply to the mainstem channel, with attendant effects on the amount and caliber of gravel stored in the channel and, therefore, the extent and quality of salmonid spawning habitat. Buer estimates that, prior to the construction of the dams, the upper Sacramento River watershed yielded an average annual coarse sediment load of approximately 50,000 cubic yards (K. Buer, 2005, personal communication). Shasta Dam was completed in 1945, so the channel downstream of Shasta Dam has been deprived of sediment from the upper watershed for six decades, resulting in a cumulative reduction of approximately 3 million cubic yards of coarse sediment.[5] In addition to the sediment trapped by the dams, nearly 7.1 million cubic yards of sediment was mined from the upper Sacramento River basin to provide construction aggregate for dam construction and related infrastructure (CDWR 1980). Kutras Park (RM 296) was one of the primary borrow areas for sand and gravel, and it provides an example of the scale and lasting effects of the aggregate extraction that supported dam construction (Figure 1).

Figure 1. Lasting effects of aggregate extraction. Kutras Park (center) was one of the primary borrow areas for aggregate to support Shasta and Keswick dam construction. More than 7 million cubic yards of sediment was mined from the upper Sacramento River basin, much of it from the mainstem channel and floodplain. Remnant mining pits can function as sediment traps

[5] Bed coarsening in the upper Sacramento River may have started before Shasta Dam was even completed in 1945. During the initial construction phases of Shasta Dam, coffer dams may have started trapping sediment from the upper watershed, so that high flow events in 1940 (186,000 cfs), 1941 (82,300 cfs), and 1942 (85,000 cfs) scoured gravel stored in the channel bed downstream of the dam site (K. Buer, 2005, personal communication).

that disrupt bedload routing, capturing spawning gravel as it is transported from upstream injection sites. (Source: CDWR, 1999. Sacramento River Aerial Atlas.)

The Sacramento River receives its first significant sediment supply from Cottonwood Creek (RM 273.5), nearly 30 miles downstream of Keswick Dam. There are several tributaries between Keswick Dam and Cottonwood Creek, but they contribute relatively little sediment to the mainstem channel, either because they drain small basins composed of resistant material, or because they are also regulated by dams and have been mined for aggregate (e.g., Clear Creek) (CDWR 1980). Similarly, much of the upper Sacramento River channel is bounded by bedrock or other erosion-resistant material (CDWR 1980), so there is little coarse sediment stored in channel banks to provide a sediment supply that attenuates the loss of sediment from the upper watershed. Shasta and Keswick dam operations have reduced the frequency of high magnitude flow events that scour gravel stored in the downstream channel bed, but they have not eliminated these flood events. Parfitt and Buer estimated that flow magnitudes of 50,000 cfs can mobilize spawning-sized gravel from the channel below Keswick Dam (1981).[6] Since the completion of Shasta Dam in the 1945, there have been several flow events with magnitudes greater than 50,000 cfs (Figure 2). With the elimination of the sediment supply from the upper watershed, these clear-water releases recruited sediment that was stored in the channel bed below Keswick Dam. Without a supply of spawning-sized gravels to replenish the material scoured and routed downstream, the channel bed surface became progressively coarser as larger lag particles, which could not be mobilized by flow releases, began to cover the bed surface. Spawning-sized gravels may be trapped beneath the coarse surface layer, but these gravels are biologically unavailable when salmon cannot mobilize the large particles that compose the armored surface.

CDFG and CDWR mapped patches of spawning habitat in the upper Sacramento River in 1964 and 1980, and a comparison of the surveys provides evidence of bed coarsening. CDWR found a loss of more than 50% of spawning habitat in the key spawning reach between ACID Dam (RM 298.4) and the City of Anderson (RM 283), ostensibly because of bed coarsening (1980) (Figure

[6] Parfitt and Buer based their estimate on observations of spawning gravel that CDFG injected in the upper Sacramento River in 1978 and 1979, the majority of which was mobilized following flood magnitudes of 36,000 cfs and 50,000 cfs in January and February, 1980, respectively. Injected gravel is often loose, unlike compacted sediment that deposits naturally in the channel; consequently, higher magnitude discharges may be required to mobilize and scour naturally deposited sediment. Also, a levee located upstream of the injection site that Parfitt and Buer monitored may have directed flows into the lobe of augmented gravel, inducing preferential scour (CDWR 1980). Nevertheless, Parfitt and Buer's estimate of 50,000 cfs as a gravel mobilization and scouring flow is based on direct field evidence, so it provides a reasonable estimate to support initial analysis.

3).[7]

Bed coarsening can be expected to propagate downstream with successive high flow events. Initially, the sediment scoured from an upstream reach will provide a sediment supply for downstream reaches, thereby attenuating the loss of sediment supply from the upper watershed. However, as in-channel storage is depleted and gravels are trapped beneath an armor layer in upstream reaches, downstream reaches will lose their sediment supply and become armored like the upstream reaches. The confluence with Cottonwood Creek likely defines the downstream limit of bed coarsening in the Sacramento River because of the sediment supplied by the creek and the reduced slope of the mainstem channel in this reach, which induces sediment deposition (CDWR 1980). Figure 3 illustrates the effect of the sediment supply from Cottonwood Creek on spawning habitat. In the reach immediately above Cottonwood Creek (RM 273.5), upstream to Balls Ferry (RM 276), there was a significant reduction in mapped spawning habitat between the 1964 and 1980 surveys—a loss of nearly 50%. In contrast, the reach below Cottonwood Creek, downstream to Jellys Ferry (RM 269), showed comparatively little change in spawning habitat between the two surveys, suggesting that the added sediment supply helped to maintain spawning habitat in this reach.

[7] During the period between the surveys, there were changes in the system that may have affected upstream passage of spawning adults (e.g., blockage caused by Red Bluff Diversion Dam beginning in 1967), which may have affected the distribution of spawning. Because the spawning habitat surveys were derived from observations of redd locations, changes in spawning distribution may have affected the amount and location of habitat mapped by the surveys. Similarly, differences in escapements during the survey periods could have affected the mapped habitat. Escapements were higher in the mid-1960s as compared with the late 1970s, so the 1964 surveys may have mapped spawning habitat that was saturated, while the 1980 survey mapped only a portion of available spawning habitat because of lower escapements. The habitat surveys also used different levels of resolution that may have affected the cumulative spawning area mapped, because the 1964 survey mapped general spawning areas, while the 1980 surveys mapped more specific patches of spawning habitat (CDWR 1980). Despite these complications, CDWR concluded that the changes in spawning habitat between the two surveys indicated a loss of habitat that reflected a trend of bed coarsening between ACID Dam (RM 298.4) and Anderson Bridge (RM 283)(CDWR 1980).

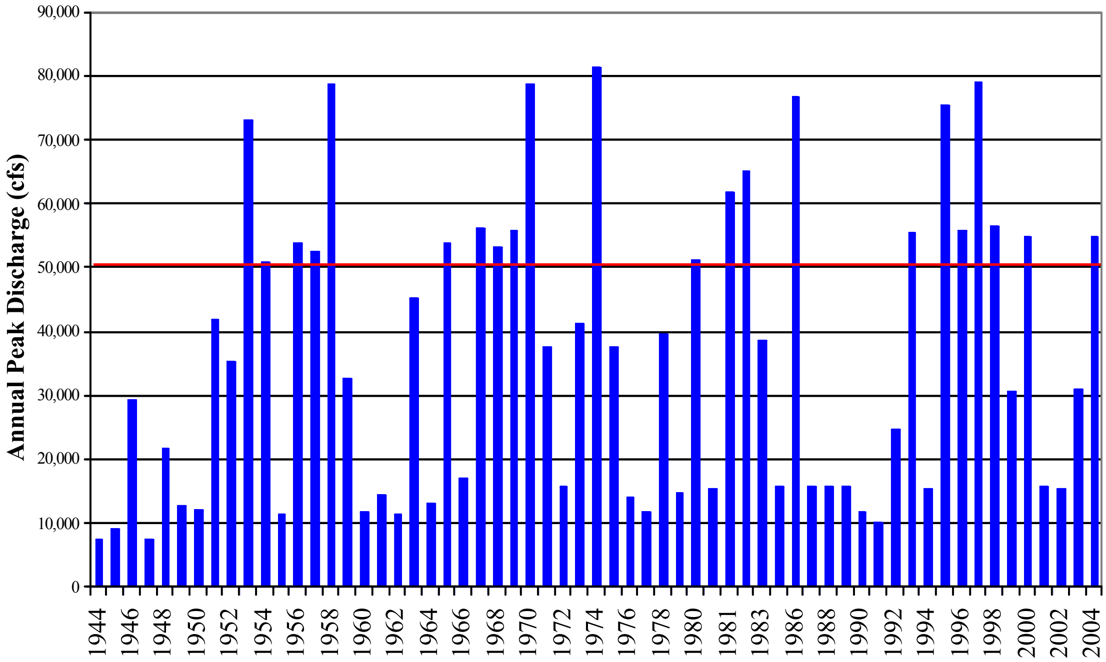

Figure 2. Bed scouring flow events. Since the completion of Shasta Dam in 1945, the USGS gauge at Keswick (no. 11370500) has registered several floods with magnitudes greater than the 50,000 cfs estimated to mobilize and scour spawning-sized gravel below Keswick Dam. Shasta and Keswick dams trap sediment from the upper watershed, depriving downstream reaches of material needed to replenish gravel scoured from the channel bed by high flow releases.

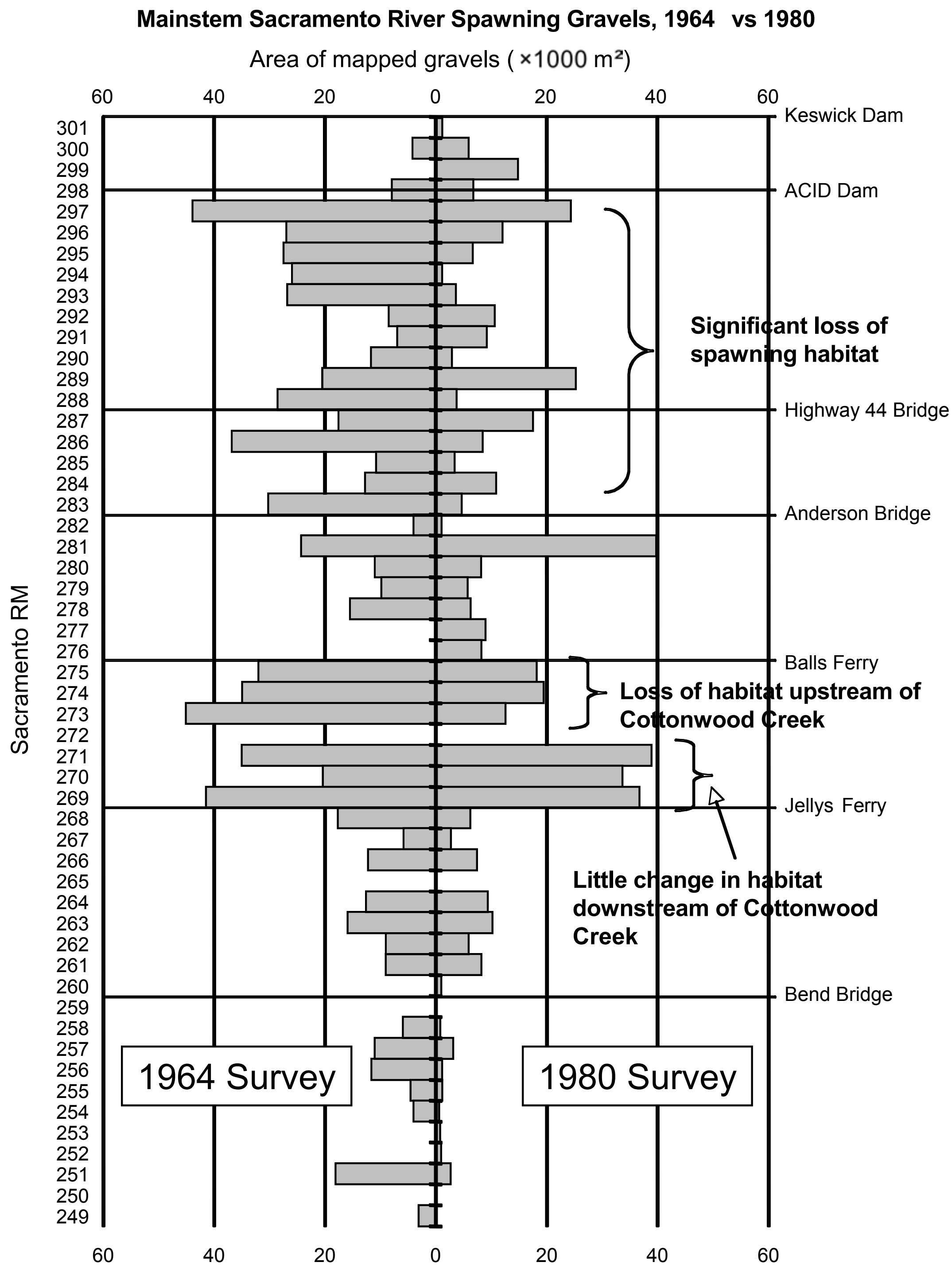

Figure 3. Change in spawning habitat. Bars on the left of the zero axis represent spawning habitat area by river mile as mapped by the 1964 survey; bars on the right of the axis show the spawning habitat area by river mile derived from the 1980 survey. Bed coarsening likely reduced spawning habitat between ACID Dam (RM 298.4) and Anderson Bridge (RM 283) between the two habitat surveys. The persistence of spawning habitat downstream of Cottonwood Creek illustrates the effects of sediment supplied by the creek.

In the Sacramento River, bed coarsening, and the downstream propagation of bed coarsening, may have been dampened periodically by the infusion of approximately 242,000 cubic yards of spawning-sized gravel since 1978 (Table 1). It is difficult to know if the scale of recent gravel augmentation has had an appreciable effect on in-channel gravel storage or the extent of spawning habitat below Keswick Dam, in light of the >10 million cubic yards of sediment that was mined from the channel and floodplain or trapped by dams. The scope and duration of the benefits derived from gravel augmentation are also uncertain because of potential sediment traps within the augmentation reach (e.g., Kutras Park at RM 296) that may break the continuity of bedload routing (CDWR 1995).

Table 1. Timing, location, and quantity of injected spawning gravel

Time frame	Location		Number of sites	Volume added yd^3
	Upstream RM	Downstream RM		
1978-1980:	298.3	297.7	3	13,300
1980-1995:	302.0	290.0	9	123,910
1995-2000:	302.0	291.6	3	105,366
Grand total:				242,576

Source: (CDWR, 2002. Cow Creek to Jellys Ferry Geomorphic Study)

Though the total volume of added gravel is small relative to the cumulative deficit of sediment since dam construction, gravel augmentation likely provided important enhancements to existing spawning habitat in the key spawning reach between Keswick Dam (RM 302) and Clear Creek (RM 289.2), where the gravel was added. However, it is difficult to assess local changes in spawning habitat using the 1964 and 1980 surveys, because the vast majority of gravel (~230,000 cubic yards) was injected after the 1980 survey was conducted. Relatively little gravel augmentation (~13,300 cubic yards) occurred between the 1964 and 1980 spawning habitat surveys, and the area where gravel was added was small, so it likely had only small, local effects on the spawning habitat that are difficult to detect by comparing the two habitat surveys.

3.2 Gravel quality

The mobilization of spawning-sized *gravel* generally requires flow magnitudes associated with periodic flood events. However, *sand and fine sediment* can be mobilized more frequently by lower magnitude flows. Grains of sand that saltate along the bed can become entrained in framework gravels, infiltrating the interstices between coarser sediment particles. As the percentage of fine sediment stored in the channel subsurface increases, intragravel flow generally decreases, which reduces habitat quality for salmonid spawning. To reduce the percentage of fine sediment stored in the channel bed, periodic flow events must have sufficient magnitude to scour the subsurface in order to expose fine sediments to downstream transport. Because lower flow magnitudes are required to mobilize sand, it will generally accumulate in the channel bed between these periodic scouring flows.

Adult salmon can clean fine sediments from gravels during redd construction by kicking subsurface fine sediments into the water column where flows can transport them downstream. However, heavy loads of fine sediment stored in the channel bed can undermine the gravel cleaning effects of redd construction. Similarly, female salmon cover deposited eggs by mobilizing sediment upstream of the egg pocket, so if the magnitude of a spawning flow is not sufficient to transport sand a significant distance downstream, then upstream sands can fill the gravel matrix of the redd, thereby muting the cleaning effects of redd construction.

In 1995, CDWR conducted a gravel study in the upper Sacramento River between Keswick Dam (RM 302) and the confluence with Cottonwood Creek (RM 273.5), which included the collection of bulk samples to characterize spawning gravel quality. Based on the bulk sampling results, CDWR concluded that fine sediment concentrations in the mainstem channel bed were not a problem above the Cottonwood Creek confluence, and that intra-gravel permeability was moderate to high throughout the reach (1995). Several factors contribute to the relatively low volume of fine sediment stored in the channel bed between Keswick Dam and Cottonwood Creek. The primary reason is decades of clear-water releases from the dams, which have reduced fine sediment stored in the channel bed by transporting it downstream. Another factor is the sediment trapping performed by Shasta and Keswick dams, which reduce not only the coarse sediment supply from the upper watershed, but also the fine sediment supply. The erosion-resistant material that bounds much of the mainstem channel in this upper reach also contributes relatively little fine sediment by bank and sheet erosion.

The concentrations of fine sediment stored in the channel bed of the Sacramento River are likely to be higher downstream of Cottonwood Creek, where a reduction in the slope of the mainstem channel, coupled with the sediment supply from Cottonwood Creek, provide conditions for fine sediment accumulation in the bed.[8]

4 STUDY OBJECTIVES AND GENERAL HYPOTHESES

4.1 Study Objectives

This study plan is designed to satisfy three general objectives defined in the Statement of Work for the Agreement between TNC and Stillwater Sciences:

1. refine estimates of flow magnitudes required to mobilize and scour sediment stored in the channel bed of the study reach (Subtask 2.1);
2. characterize gravel and its habitat value for salmonids in the study reach (Subtask 2.3); and
3. provide data for sediment transport simulation with The Unified Gravel-Sand (TUGS) model (Subtask 3.1).9

To satisfy these objectives, this gravel investigation includes new analyses of existing data and the collection of new field data that builds on previous research efforts. For example, CDWR conducted gravel studies in the upper Sacramento River in the 1980 and 1995, and in the middle Sacramento River in 1984. Much of the data produced by these previous efforts can be used as model input for the TUGS model, and new field data can be compared with these existing datasets to identify trends in channel bed composition. Similarly, CDFG and CDWR mapped spawning habitat in the Sacramento River in 1964 and 1980, and digitization of these maps can support a more detailed, GIS-based analysis of changes in spawning gravels over time.

[8] Fine sediment concentrations in the Sacramento River may also be higher in the reach immediately upstream of Cottonwood Creek because of a backwater effect caused in the mainstem channel during high flow periods in Cottonwood Creek, which may induce sediment deposition in the mainstem channel.

[9] The Unified Sand-Gravel (TUGS) model is a sediment transport model developed by Stillwater Sciences that predicts surface and subsurface grain size distributions as a function of flow and sediment supply.

Previous investigations have developed estimates of the flows required to mobilize, scour, and route sediment for different reaches of the mainstem Sacramento River (Goal 1) (CDWR 1980, 1984, 1995). However, many of these flow estimates are provisional because of the difficulty collecting field data in a river as large as the Sacramento River, or they need to be updated because channel changes in an altered system like the Sacramento River can alter geomorphic thresholds. As a result, this gravel investigation includes field studies and sediment transport modeling to estimate the flow required to mobilize and route sediment. Similarly, there has been even more effort to characterize gravel in the mainstem channel (Goal 2) (Bigelow, 1996; CDWR 1980, 1984, 1992, 1995, 2002), but gravel characteristics change with time as a function of high flow events and changes in sediment supply. This study includes the collection of new field data to characterize current spawning habitat characteristics. These previous research efforts also provide sediment data that will be useful input for the TUGS model (Goal 3), but previously collected data may not reflect current conditions in the Sacramento River because of changes in sediment supply and in-channel storage since this data was collected.

4.2 Hypotheses

In addition to collecting and analyzing data to identify the character and dynamics of spawning-sized gravel in the mainstem Sacramento River, several study components are also designed to test more specific hypotheses that have been developed as part of the SOS Report (Stillwater Sciences 2006). These hypotheses spring from the conceptual models summarized in Section 3.[10]

4.2.1 Hypothesis #1: Progressive bed coarsening has further reduced the extent of salmonid spawning habitat between ACID Dam (RM 298.4) and Anderson Bridge (RM 283).

As described in Section 3.1, comparison of the 1964 and 1980 spawning habitat maps suggests a significant loss of spawning habitat between ACID Dam (RM 298.4) and Anderson Bridge (RM 283), presumably because of bed coarsening. Decades of clear-water, high flow releases scoured gravel from the channel below Keswick Dam, and the elimination of sediment supply from the upper watershed, coupled with the limited sediment supply from tributaries and banks, deprived the reach of the gravel needed to maintain in-channel sediment storage. Over time, more of the bed surface became armored by large lag particles that could not be mobilized by high flows, trapping finer sediment in the subsurface. The remaining spawning habitat in the channel reflects relict features (e.g., point bars) in zones were local hydraulics prevent high flows from eroding gravels (CDWR 1995).

Previous investigators have hypothesized that the bed of the upper Sacramento River coarsened in the post-Shasta era, and field studies have provided some evidence to support the hypothesis (CDWR 1980, 1995; USFWS 1996). However, it is not clear if bed coarsening has intensified in the mainstem channel, or if gravel augmentation has ameliorated in-channel gravel storage between ACID Dam (RM 298.4) and Anderson Bridge (RM 83). Recent field studies have produced ambiguous results. For example, CDWR conducted Wolman pebble counts in the upper

[10] These hypotheses are not "null" hypotheses in the strict statistical sense. Rather, they are more general articulations of key process-habitat-biota linkages that can be tested by analysis.

Sacramento River in 1980 and 1995. In the interval between the surveys, nearly 124,000 cubic yards of gravel was added to the reach between Keswick Dam (RM 302) and Clear Creek (RM 289.2). CDWR compared the pebble counts from the 1980 and 1995 surveys and found that the channel bed in some locations had become coarser, but other sites had grown finer, and one reach had changed little (CDWR 1995). Therefore, it was difficult to tell if the channel bed had continued to coarsen, or if gravel augmentation had improved in-channel gravel storage and spawning habitat. CDWR also collected bulk samples in 1980 and 1995, and a comparison of the surveys suggested that all of the sampled reaches had grown more coarse despite the added gravel; however, the strength of this conclusion was limited because the number of samples collected was small and CDWR used different sampling methods in each survey, (CDWR 1995).

We hypothesize that bed coarsening has continued in the upper Sacramento River between ACID Dam and Anderson Bridge, and that spawning habitat has been further reduced in this reach, despite recent gravel augmentation.

This hypothesis suggests that the scale of gravel augmentation to date has provided local and short-term benefits for spawning habitat in the vicinity of the injection site, but has done little to enhance downstream spawning areas as it is routed.

Imported gravel is generally more susceptible to recruitment and routing than sediment that deposits naturally in the channel, because the added gravel usually has a more homogeneous grain size distribution and it is not compacted. Of the 13,300 cubic yards of spawning-sized gravel added to the upper Sacramento River in 1978 and 1979, CDWR estimated that 85% of it was eroded by high flow events of 36,000 cfs and 50,000 cfs in the winter of 1980. In comparison, relatively little of the non-imported sediment at the same site (e.g., gravel that had deposited naturally in the channel) was scoured (CDWR 1980). There have been several high flow events with a magnitude greater than 50,000 cfs during the period of gravel augmentation (1978 – 2001), and many of these flows likely recruited the imported gravel and routed it downstream.

Gravel routing is a valuable ecosystem process that is essential for creating and maintaining aquatic habitats, but we hypothesize that several factors have limited the habitat benefits of imported gravel that is routed downstream. First, the scale of gravel augmentation implemented to date (~243,000 cubic yards) is small when compared to the cumulative volume of coarse sediment eliminated from the upper watershed by dams (> 3 million cubic yards), mined from the basin (> 7 million cubic yards) and scoured from the channel bed in the post-dam era. From a landscape-scale perspective, recent gravel additions have provided only a small increase in sediment supply and in-channel sediment storage, so it has likely had little effect on cumulative spawning habitat area in the upper Sacramento River.

The real benefit of gravel augmentation has occurred at the local scale, where the added sediment has provided important, but short-term, enhancement of patches of spawning habitat located near the injection sites. The small tributaries that contribute modest sediment loads to the mainstem channel (e.g, Cow Creek, Stillwater Creek) provide an example of the local benefits of gravel augmentation. The 1964 and 1980 habitat surveys show that spawning habitat located near tributary confluences either increased or remained stable between the surveys, demonstrating the importance of even a small gravel supply in maintaining local patches of spawning habitat (Figure 4). However, the small sediment loads supplied by the tributaries between Keswick Dam and Cottonwood Creek did little to maintain spawning habitat farther downstream, where habitat area was reduced between the two surveys. Recent gravel injections can be expected to produce similar effects—helping to maintain local patches of existing spawning habitat located near the injection sites, with little effect on habitat farther downstream. The added gravel likely enhances or maintains local patches of habitat by depositing in the nearby relict features (e.g., point bars) that constitute the remaining spawning habitat in the upper Sacramento River, either increasing gravel depth or adding habitat along the margins of the relict feature.

As the imported gravel is routed downstream, it may not improve or expand spawning habitat because it deposits in thin lenses of insufficient depth to support spawning, because it deposits in areas that are not hydraulically suitable to support spawning, or because it is intercepted by sediment traps. For example, CDWR observed areas where spawning-sized gravels composed a significant portion of the channel bed surface, but hydraulic conditions seemed outside of the range preferred by salmonids (CDWR 1995). Similarly, at least 25% of the gravel added to the upper Sacramento River has been injected below ACID Dam (RM 298.5) but upstream of large remnant mining pits located between RM 295 and RM 298 that may trap gravel moving as bedload during high flow events (CDWR 1995).

Because gravel augmentation (at the scale implemented to date) and the sediment supply from small tributaries seem to have only local effects on spawning habitat, in-channel coarse sediment storage in other reaches of the channel has likely decreased since the 1980 spawning habitat survey as a function of scouring flows. Consequently, cumulative spawning habitat has likely decreased between ACID Dam and Anderson Bridge despite the addition of 242,000 cubic yards of gravel to the reach.

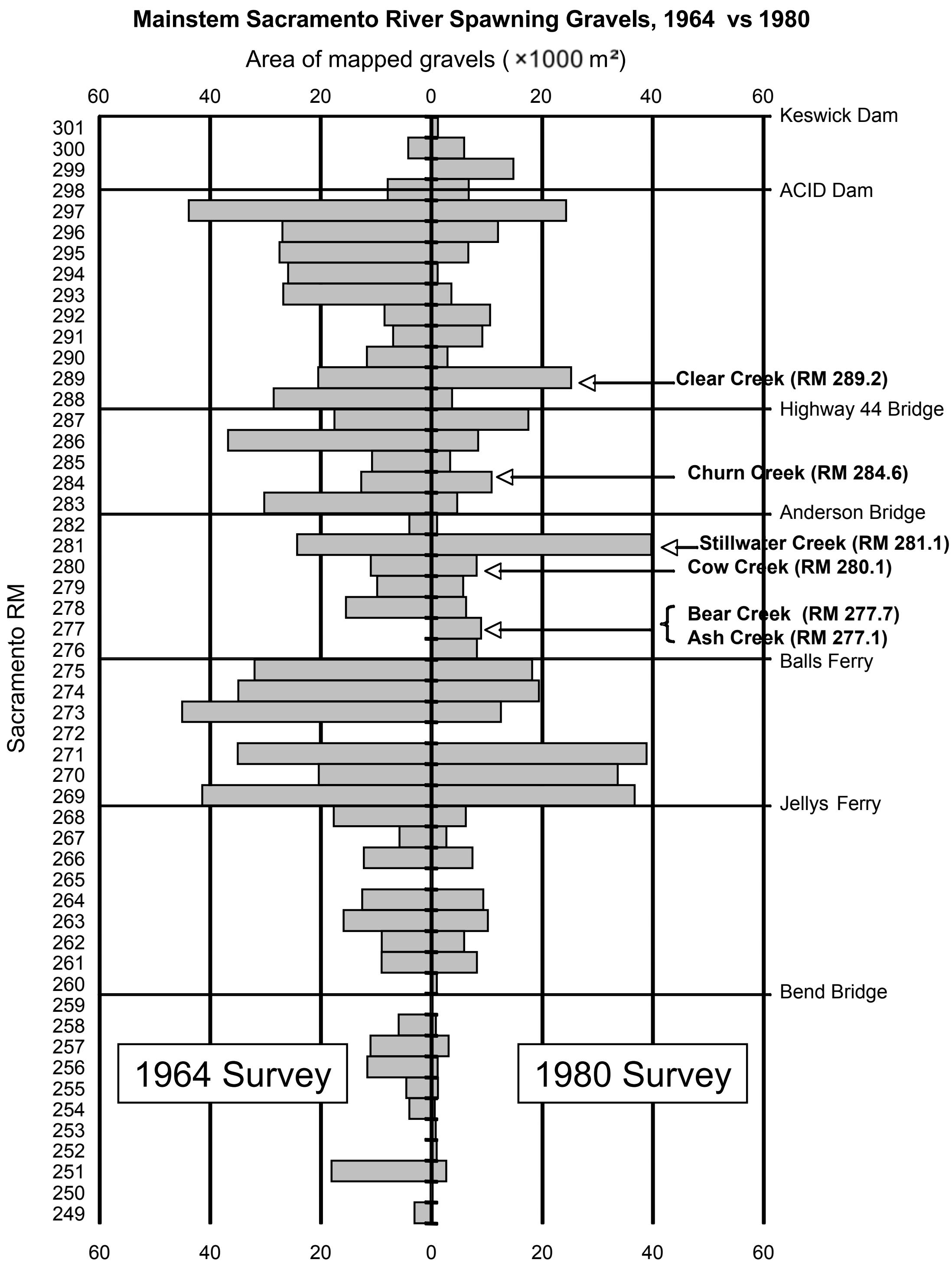

Figure 4. Local effects of small gravel additions. Several tributaries contribute small amounts of sediment to the mainstem channel, helping to maintain patches of spawning habitat near the confluence. However, the small sediment supply produces only local effects, having little impact on the maintenance of spawning habitat farther downstream. Gravel augmentation may create a similar pattern, helping to maintain existing habitat near the injection site, but doing little to expand spawning habitat farther downstream.

4.2.2 Hypothesis #2: Channel bed coarsening has been migrating progressively downstream below Keswick Dam.

As described in Section 3.1, gravel scoured from the channel bed below Keswick Dam initially provided a sediment supply to reaches farther downstream. As in-channel storage was exhausted in upstream reaches, bed coarsening likely propagated downstream as successive high flow events scoured sediment from the channel bed farther and farther downstream, with little sediment supply to replace the mobilized material. As described in Section 4.2.1, we hypothesize that gravel augmentation, and the relatively small sediment supply from tributaries between Keswick Dam and Cottonwood Creek, likely helped to maintain local patches of existing spawning habitat located near the injection sites and tributary confluences. However, the small scale of sediment supply in this reach probably did little to maintain or expand spawning habitat *between* the injection sites and tributary confluences.

We hypothesize channel bed coarsening has propagated downstream so that spawning habitat has been reduced between Anderson Bridge (RM 283) and Cottonwood Creek (RM 273.5).

There is little existing data to test this hypothesis. We can use the 1964 and 1980 spawning habitat maps to document that bed coarsening occurred between the surveys, but another habitat survey would be required to track any downstream movement of bed coarsening.

Though there are several small tributaries that contribute sediment to the mainstem channel in the reach between Anderson Bridge and Cottonwood Creek (Figure 4), there have been several significant flow events in the mainstem Sacramento River since 1980 that we hypothesize have caused significant scouring, thereby undermining the local maintenance of spawning habitat located near the tributary confluences and accelerating bed coarsening in the intervening reaches. The reach below Cottonwood Creek has likely remained stable despite the number of high flow events because of the more significant sediment supply, which may have increased since 1980 as gravel mining on Cottonwood Creek has been regulated more carefully. The channel bed below Bend Bridge (RM 260) may not have coarsened significantly since 1980, because the significant loss of spawning habitat between the 1964 and 1980 surveys suggests that remaining habitat is associated with relict features in zones where local hydraulics help prevent high flows from further eroding gravel.

This hypothesis has key implications for the population dynamics and management of fall-run Chinook salmon. As with the other salmonid runs in the Sacramento River, fall-run salmon have experienced a general population decline in the last three decades; nevertheless, they still have the highest escapement rates of the Central Valley salmonids, in large measure because their life history timing grants them access to comparatively more spawning habitat. Fall-run spawning occurs at a time (mid-October to mid-December) when both air and water temperatures are declining, so as the spawning season progresses, more spawning habitat becomes available as suitable water temperatures extend farther downstream. Annual redd surveys conducted by CDFG confirm that fall-run Chinook salmon spawning in the mainstem channel is distributed more widely than that of the other runs, often stretching as far downstream as Princeton (RM 163). In comparison, the downstream extent of late-fall-run Chinook spawning is usually Red Bluff Diversion Dam (RM 243), and winter-run salmon typically spawn above the Highway 44 Bridge (RM 288).

Fall-run Chinook salmon are a federal species of concern, and further declines in escapements could prompt the need for protection, which could intensify conflicts between environmental flow needs and other beneficial uses of water. As described in section 3.1, an analysis of the 1964 and 1980 spawning habitat maps indicates a loss of spawning habitat between ACID Dam (RM 298.4) and Anderson Bridge (RM 283), presumably as a function of bed coarsening. As with the other salmonid runs, this loss of habitat likely contributed to the decline in fall-run Chinook salmon escapements, but fall-run access to downstream spawning areas likely tempered the loss of spawning habitat relative to other salmonid species, which helped to keep fall-run salmon escapements comparatively higher. However, the downstream propagation of bed coarsening could have more significant effects on fall-run Chinook salmon because they are the only run to spawn in substantial numbers in downstream riffles. The SOS Report (Stillwater Sciences 2006) also explains that the life history strategy of fall-run Chinook salmon makes them particularly vulnerable to spawning habitat losses, because they need to produce relatively higher numbers of offspring to offset proportionally higher rates of juvenile mortality, as compared with other salmonids.

4.2.3 Hypothesis #3: The percentage of fine sediment stored in the subsurface is higher in the reach downstream of Cottonwood Creek.

High concentrations of fine sediment stored in the subsurface can reduce salmonid spawning habitat quality by reducing intragravel flow, which is necessary to deliver dissolved oxygen to incubating eggs and transport metabolic waste from the egg pocket. Because sand (< 2mm) can be mobilized by relatively low flow magnitudes, it will generally accumulate in the channel bed during the intervals between periodic flood events that scour gravels and expose the subsurface fines to transport. As described in Section 3.2, bulk sampling conducted in 1995 by CDWR between Keswick Dam (RM 302) and Cottonwood Creek (RM 273.5) indicated that this upstream reach had relatively low rates of fine sediment infiltration and moderate to high rates of gravel permeability. **We hypothesize that fine sediment concentrations are higher in the mainstem channel below the confluence with Cottonwood Creek** because of the combination of increased sediment supply from the creek and the reduced slope of the mainstem channel in this reach. Because fall-run salmon are the only salmonid to spawn in substantial numbers below the confluence with Cottonwood Creek, they are the most vulnerable to fine sediment accumulation in the mainstem channel bed. A decrease in spawning habitat quality below Cottonwood Creek has important management implications, because it can combine with the loss of habitat extent caused by the downstream propagation of bed coarsening to put pressure on the mainstem spawning population of fall-run salmon. Further declines in fall-run escapements could necessitate listing under the Endangered species Act, which could intensify conflicts for beneficial water uses. High concentrations of fine sediment in the mainstem channel could also indicate the need for more frequent high flow events to scour gravels and expose subsurface fine sediments to downstream transport.

5 ANALYSES

We can conduct several analyses using existing data, in combination with new tools, to test the hypotheses described in the previous section.

5.1 Assess the bed coarsening hypothesis by comparing mapped spawning habitat between the 1964 and 1980 mapping surveys.

CDWR analysis of the 1964 and 1980 spawning habitat surveys occurred before the widespread availability and use of Geographical Information Systems (GIS). Stillwater Sciences has digitized the 1964 and 1980 spawning survey maps and incorporated them in a GIS, which facilitates more detailed analysis of changes in spawning habitat. Stillwater Sciences conducted a GIS-based analysis of the spawning habitat surveys as part of the SOS Report, which is summarized in Section 3.2 and illustrated in Figure 3. As part of the gravel study, Stillwater Sciences will use the GIS to conduct more detailed analysis of the digitized spawning maps in order to test the bed coarsening hypothesis by using smaller spatial bins than the one-river-mile resolution used for the SOS Report.

The higher spatial resolution will allow us to examine more local changes in mapped spawning habitat, with an explanation of the factors influencing those local changes. For example, we will examine more specifically how tributary contributions of sediment and gravel injection affect local changes in spawning habitat and the downstream limit of those effects. Similarly, we try to locate and account for the effects of potential sediment traps (e.g., remnant mining pits, deep pools) in the channel that may disrupt bedload routing and exacerbate spawning habitat loss in reaches downstream of the traps. Better accounting of gravel sources and sinks can allow us to examine the mechanisms underlying observed trends in spawning habitat and channel bed composition.

5.2 Analysis of existing grain size data to test the bed coarsening hypothesis

CDWR collected grain size information on the upper Sacramento River in 1980 and 1995, including numerous Wolman pebble counts and several bulk samples in which the surface was processed separately from the subsurface. We conducted an initial examination of this grain size information for the SOS Report; however, this initial analysis relied primarily on *plots* of grain size information, rather than an analysis of raw data. Comparing the grain size distributions from the two surveys suggests that the channel bed at many of the sampling sites grew coarser between the surveys. However, the *plots* of grain size information do not permit a more detailed analysis of the mechanism underlying the change in the grain size distributions. For example, the shift in the grain size distributions may indicate that the channel bed coarsened as high flows scoured *gravels*, leaving behind larger lag particles that could not be mobilized; however, it could also suggest that high flow events reduced the amount of *sand* stored in the channel bed. The change in grain size distributions likely reflect both mechanisms at work, but the existing data plots will not support additional analysis that would allow us to assess the relative magnitude of each mechanism. Determining the relative importance of each mechanism provides a potential test of the bed coarsening hypothesis. If grain size distributions grew coarser primarily because of a reduction of fine sediment stored in the channel bed, then this could suggest that bed coarsening is not as severe as has been hypothesized and that other factors (e.g., changes in upstream passage, differences in escapements during the survey years) have driven the changes in mapped spawning habitat. It could also suggest that remaining spawning habitat has been improved by increasing intra-gravel flow. However, if the change in grain size distributions primarily reflects the erosion of spawning size gravel from the channel bed, then this provides further evidence that changes in mapped spawning habitat can be ascribed to bed coarsening.

Access to the raw grain size information would allow us to isolate trends in both the coarse and fine fractions of sediment. For example, if we excluded all sediment < 2mm from the dataset, we could examine the trend in the coarse fraction to examine the extent to which the bed became more coarse because of the erosion of spawning-sized gravels. Similarly, we could exclude all sediment > 2mm from the dataset to examine the trend in fine sediment storage reflected between the two surveys. Conducting these analyses requires the full datasets of grain size information collected by CDWR, rather than the plots published in the reports. We have obtained the raw data for the 1995 survey from CDWR, but they have not been able to locate the raw data from the 1980 survey thus far. If we cannot obtain the raw data from the 1980 survey, then this study component will need to be abandoned. Nevertheless, the 1995 grain size information will still support an analysis of trends in sediment stored in the channel bed when combined with the new bulk sampling that Stillwater Sciences will conduct in 2005 (described in Section 6.2).

If we do obtain the raw data from the 1980 bulk sampling survey, then this analysis will have to account for a couple of confounding factors. State and federal agencies injected approximately 124,000 cubic yards of spawning sized gravel to the upper Sacramento River between the 1980 and 1995 surveys, as part of a conservation effort for winter-run Chinook salmon. If the gravel injection sites are located in, or just upstream of, the 1995 sampling sites, then the grain size data for particular locations may reflect the addition of finer sediment. Also, the 1980 and 1995 surveys used different bulk sampling methods. In 1980, the surveys were conducted using 12" McNeil samples, but the 1995 surveys used 3' x 3' plots of shovel samples. In addition to the difference in the **size** of the samples produced by the two different methods, the 1980 survey may reflect a sampling bias for finer grain sizes, because the narrow gauge of the McNeil sampler may have encouraged investigators to avoid sampling areas with coarse material.

5.3 Sediment transport modeling to test the bed coarsening hypothesis

Stillwater Sciences has developed a new sediment transport model that predicts changes in surface and subsurface grain size distributions, including the fraction of sand stored in the bed, based on flow events and sediment supply. TUGS model was developed primarily to simulate the effects of different management actions (e.g., changes in the flow regime, gravel augmentation) on spawning habitat quality by predicting the percentage of fine sediment stored in the channel bed and reach-averaged values of grain size. The results of these simulations will be incorporated into the DA Tool.

We will also use TUGS model to test the bed coarsening hypothesis by simulating the evolution of the channel bed below Keswick Dam following the construction of Shasta Dam. This model simulation will start with an initial grain size distribution that represents the channel bed at the time of dam completion in 1945, and it will use existing slope and channel geometry data to model the effects of historical flows (as measured by USGS gauge data) on channel bed composition. The model will predict grain size values of the channel bed through time, reflecting the scour of sediment caused by historical high flow events and the elimination of the sediment supply from the upper watershed. The goal of this simulation is to reproduce the trend of the bed evolution following Shasta Dam closure (e.g., to see if the predicted bed becomes more coarse) and to re-create the conditions that result in the current channel bed as indicated by CDWR grain size data (1980, 1995).

We have not found any historical grain size information that characterizes channel bed composition at the time of dam completion; therefore, we will have to make some assumptions about the grain size distribution of the initial bed. We can model the evolution of the channel bed using several different grain size distributions that reflect different hypothesized bed conditions at the time of dam completion. If the TUGS model simulations indicate shifts in the grain size distribution as a function of historical high flow events, then the exercise will provide further evidence that the observed loss of spawning habitat was probably caused by bed coarsening rather than some other factor.

6 FIELD STUDIES

The field studies provide the primary mechanism for achieving the objectives of the gravel study: estimating the flows required to mobilize and scour gravel; characterizing the spawning habitat quality; and providing grain size information for TUGS model. The field studies also provide opportunities to test the hypotheses described in Section 4.2.

6.1 Wolman Pebble Counts

Wolman pebble counts are a method for quickly characterizing the surface of a channel bed. Pebble counts involve selecting individual sediment grains from the bed surface of a sample area and measuring its b-diameter to determine the grain size (Wolman 1954). The resultant dataset allows a researcher to plot grain size distributions to characterize the bed surface. We will conduct pebble counts in several reaches of the Sacramento River to characterize the bed surface of salmonid spawning areas. The resultant grain size plots will help us to determine if many of the current spawning areas are composed of particle sizes that fall safely within the range preferred by salmonids, or if the bed surface falls within the coarse end of the spectrum and is therefore in danger of becoming lost as spawning habitat by future bed coarsening. Wolman pebble counts will contribute to the study objective of characterizing the habitat value of spawning areas.

Repeated application of pebble counts in different years can also support an analysis of trends in the bed surface, and because several pebble counts have been conducted in the Sacramento River since 1980 (CDWR 1980, 1984, 1995, 2001), the collection of a new pebble count dataset will also allow us to test the bed coarsening hypothesis. In the reach above Cottonwood Creek (RM 273.5), CDWR sampled several sites in multiple years as part of the previous pebble counts (Table 2), and we compared these datasets to identify trends in bed surface composition for the SOS Report. However, most of the sites that could support an analysis of trends (e.g., had been sampled multiple times) were only sampled twice, and many of these sites were located near tributary confluences where the addition of sediment helps to maintain small islands of spawning areas that may not be representative of the reaches between tributary confluences. As a result, it was difficult to identify a clear trend in the upper Sacramento River bed surface, though some sites indicated the occurrence of bed coarsening.

Sampling Area

Because pebble counts provide a means of characterizing the bed *surface*, we will focus pebble counts between ACID Dam (RM 298.4)[11] and Cottonwood Creek (RM 273.5), which is the reach where we hypothesize bed coarsening has been occurring.[12] We will also conduct pebble counts below Cottonwood Creek to assess if bed coarsening has occurred downstream and to test the hypothesis that Cottonwood Creek defines the downstream limit of bed coarsening, but the bulk

[11] Site access, water depth, and high flow velocities make it difficult to sample the reach between Keswick Dam (RM 302) and ACID Dam (RM 298.4).

[12] Bed coarsening is a surface process, by which large particles begin to cover the bed. Even if the subsurface is composed of spawning-sized sediment, adult salmonids cannot access this material if they cannot mobilize a surface armored by coarse particles.

of the pebble counts will be conducted above Cottonwood Creek. We will collect pebble counts in locations that CDWR has sampled in the past so that we can leverage existing datasets to analyze trends in the bed surface (Table 2). Because of potential changes in channel alignment and the location of geomorphic features (e.g., point bars) since the previous pebble counts were conducted, we will select sample sites that are geomorphically similar to previously sampled sites, rather than sampling the exact locations. We will collect a minimum of 15 pebble counts between ACID Dam (RM 298.4) and Cottonwood Creek (RM 273.5) and a minimum of 5 pebble counts below Cottonwood Creek.

Methods

Field scientists will use maps identifying the location of previous pebble counts conducted by CDWR in conjunction with recent aerial photographs of the upper Sacramento River to select sampling locations that are geomorphically similar to those that have been sampled previously. In the field, scientists will select a wadeable area of the bed surface that is representative of the surrounding channel bed. Using a grid pattern, scientists will select individual grains of sediment blindly from the sample area and use a measuring stick to measure the b-axis of the sediment particle to the nearest millimeter. Each measurement will be recorded in a waterproof field notebook or datasheet in the appropriate grain-size class that corresponds to integer increments on the phi scale (i.e., <4 mm, 8 mm, 16 mm, 32 mm, etc.). Once each measurement has been recorded, the sediment particle will be thrown from the sampling area to prevent it from being re-sampled.

Sampling Dates

Pebble counts will be conducted in October and November, 2005, which is the period when flows typically recede as a function of reduced water supply deliveries and the expiration of seasonal water temperature management requirements. This sampling period generally occurs before winter rains that can cause increases in flow and turbidity that complicate field sampling. Sampling during autumn base flows will allow researchers to wade farther into the channel to conduct surveys in areas that are inundated perennially, rather than being limited to the channel margins in zones that may be seasonally dry.

Table 2. CDWR sampling sites in the mainstem Sacramento River between Keswick Dam and Cottonwood Creek. The number of Wolman pebble counts collected at each location are displayed for each corresponding gravel survey. Bulk sampling sites for 1980 and 1995 are highlighted in bold.

Approximate RM	Number of surface samples by year			Site Name
	1979–80	1995	2001	
301.7	1			Keswick
300.4	1			Salt Creek
299.8	1			above Lake Redding
298.7	2			Lake Redding
298.3	**1**	**1**		**Caldwell Park**
296.9	**3**	**1**		**Turtle Bay Upstream**
296.1	2			Turtle Bay Downstream
294.8	2			Cypress
294.3	1			no name 1
293.0	1			below Beaver Bay
292.7	**2**	**1**		**across from Golf Course**
292.2	1			above Tobiasson
291.7	1			Tobiasson
291.3	**3**	**3**		**below Tobiasson**
290.8	2			no name 2
289.9	1			below Shea Levee
289.1	**6**	**1**		**Clear Creek Confluence**
288.1	**3**	**1**		**above I-5 embankment**
287.3	**1**	**1**		**at I-5 embankment**
286.6	1			below I-5 embankment
286.3	**2**	**1**		**no name 3**
285.2	1			under I-5 Bridge
284.5	2			above Churn Creek
284.2	2			Churn Creek
283.1	4		1	below Churn Creek
282.6	**1**	**2**		**Anderson outfall**
281.8	7		1	Stillwater cutoff
281.1	**13**	**1**		**Stillwater Creek**
280.2	**7**	**1**	**1**	**Cow Creek**
279.1	**2**	**1**	**1**	**below Cow Creek**
278.7	3		1	no name 3
278.3	**3**	**1**		**above Bear Creek**
277.6	3			Bear Creek
277.3	1			below Bear Creek
277.1	3			Ash Creek
276.9	3			below Ash Creek
275.7	**2**	**1**	**1**	**Anderson Creek**
273.3	**5**	**3**	**2**	**Cottonwood Creek**
Total number of samples:	100	20	8	

6.2 Bulk Sampling

Bulk sampling is a method for characterizing the sediment composition of both the bed surface and subsurface by collecting a plug of sediment and sieving the sample to separate the sediment particles into grain size classes. Each grain size class is then weighed to determine what percentage of the total mass it constitutes. Researchers can use the resultant dataset to plot grain size distributions to characterize the channel bed. The results of the bulk sample surveys will be used as model input for the TUGS model, thereby contributing to one of the study objectives. The bulk sample surveys will also contribute to the study objective of characterizing habitat quality in spawning areas, because they provide a means for assessing the percentage of fine sediment stored in the channel bed, which can be used as an indicator of spawning habitat quality. As the percentage of fine sediment stored in a channel bed increases, interstitial flow generally decreases, which can disrupt the delivery of dissolved oxygen to incubating eggs and the removal of metabolic wastes from the egg pocket.

Sampling Area

We will focus the bulk sampling surveys in the Sacramento River below Cottonwood Creek (RM 273.5), which is the reach where we hypothesize that fine sediment storage in the channel bed is higher because of the sediment supply from Cottonwood Creek and the reduced slope of the mainstem channel in the reach. CDWR collected bulk samples at several sites between ACID Dam (298.4) and Cottonwood Creek (RM 273.5) in 1980, 1995, and 2001, and each survey indicated that the percentage of fines stored in the subsurface was relatively low, such that gravel permeabilities were moderate to high in this upstream reach. Considering the cost and time required to collect and process bulk samples, it is more valuable to focus bulk sampling downstream of Cottonwood Creek where fine sediment storage likely has a larger influence on spawning habitat quality, rather than collecting another set of bulk samples above Cottonwood Creek. However, we will collect at least two bulk samples from the mainstem channel above Cottonwood Creek, and at least one bulk sample immediately downstream, to test the hypothesis that fine sediment concentrations increase downstream of the confluence.

We will collect a minimum of six bulk samples from the mainstem channel below Cottonwood Creek. We will select sampling locations that correspond with some of the sites where CDWR previously collected bulk samples in 1984, so that we can compare grain size distributions to identify potential changes in channel bed composition (Table 3).

Table 3: River-mile Locations of Previous CDWR Bulk Sampling Sites below Cottonwood Creek (CDWR 1984)

242.7	233.0	218.6	201.8
240.4	228.3	215.3	197.9
238.5	225.6	211.6	163.5
236.1	221.2	208.9	

There have been significant changes in channel alignment and geomorphic features (e.g., point bars) in the part of the river where we will collect the majority of the bulk samples; consequently, we will have to sample geomorphically similar sites that are located near those that CDWR sampled in 1984, rather than the exact locations. CDWR focused their bulk samples at the head of point bars, which is the location where the majority of spawning was observed.

Methods

Field scientists will use maps identifying the location of previous bulk samples collected by CDWR in conjunction with recent aerial photographs of the middle Sacramento River to select sampling locations that are geomorphically similar to those that have been sampled previously. At each sampling site, scientists will select a wadeable area of the bed surface that is representative of the surrounding channel bed and push a 36-inch diameter metal culvert into the channel bed to define the sampling area. The culvert helps to deflect flow so that fine sediments are not transported downstream during the process of excavation. Retaining the fine sediments in the sample is important because the percentage of fine material stored in the channel bed is an important model input for the TUGS model.

At each sampling site, we will process the surface and subsurface separately so that we can plot grain size distributions for each. During data analysis, we will also combine the surface and subsurface data to develop a grain size distribution for each full sample. To define the depth of the surface, field scientists will identify the largest sediment particle exposed on the bed surface within the sample area defined by the culvert. The b-axis of that particle will define the general depth of the surface layer. We will excavate the surface layer with metal scoops and by hand, and the surface layer sample will be deposited in buckets that will be hauled to the bank for sieving. Once the surface layer is removed, we will excavate the subsurface using metal scoops and round-nose shovels, and the subsurface sample will be deposited in buckets and transported to the bank for processing. The depth of the subsurface sample to be excavated will be scaled to the largest particle size recorded in the surface sample.

The surface and subsurface samples will be sieved on site using US standard sediment sieves. Each sample will be washed as it is processed through each sieve to ensure that fine sediment does not adhere to larger sediment particles. The smallest sieve used in the field will be #4, with a mesh screen size of 4.76 mm (0.187 in). The coarse sediment classes will be weighed on site and recorded in a waterproof field book or datasheet.

For all sediment passing through the #4 sieve, we will record a wet weight and then mix the sediment on a tarp and collect at least a 1 kg subsample of the material for drying and sieving in a laboratory. The subsample will be dried in a kiln and weighed to develop a relationship between the wet weight of the full sample recorded in the field and the dry weight of the subsample. The dried subsample will then be sieved using US standard small gauge sediment sieves.

Sampling Dates

Bulk sampling will be conducted in October and November, 2005, which is the period when flows typically recede as a function of reduced water supply deliveries and the expiration of seasonal water temperature management requirements. This sampling period generally occurs before winter rains that can cause increases in flow and turbidity that complicate field sampling. Sampling during autumn base flows will allow researchers to wade farther into the channel to collect samples in areas that are inundated perennially and more representative of salmonid spawning habitat, rather than being limited to the channel margins in zones that may be seasonally dry.

6.3 Permeability sampling

Though bulk samples provide an effective method for characterizing salmonid spawning habitat quality, they require significant time and resources to conduct, so researchers are often limited to collecting one sample to represent a large area, and the total number of samples collected is often small. Permeability sampling provides another method for assessing spawning habitat more quickly. To collect permeability measurements, field scientists drive a permeability standpipe to a defined depth in the channel bed. They insert a sipping rod into the standpipe, and an electric pump attached to the sipping rod draws water from inside the standpipe, which causes water flowing through the bed subsurface to stream through small holes drilled in the standpipe. By measuring the time required to collect a defined volume of water, we can derive a coarse measure of interstitial flow rates. Because permeability standpipes are usually several feet in length, it is possible to sample deeper parts of the channel than can usually be surveyed by bulk sampling, which allows us to characterize a broader range of spawning habitat.

Sampling Area

CDWR conducted permeability measurements in the Sacramento River above Cottonwood Creek and recorded permeability rates that ranged from moderate to good (1995), reflecting the low volume of fine sediment that is stored in the channel bed between Keswick Dam and Cottonwood Creek. We will focus permeability sampling in salmonid spawning areas downstream of the Cottonwood Creek confluence, where in-channel fine sediment storage is likely to be higher because of the increased sediment supply from Cottonwood Creek, and because of heavier agricultural activity in the middle Sacramento River, which can increase erosion rates and fine sediment loading. However, we will sample at least two sites upstream of Cottonwood Creek to test the hypothesis that fine sediment concentrations are higher, and therefore permeability rates are lower, downstream of the confluence.

We will co-locate permeability sampling with the bulk sampling, so that we can compare permeability rates with the grain size distributions produced by the bulk samples. Sampling the same areas using both methods will allow us to examine relationships between permeability and the percentage of fine sediment stored in the bed. Generally, there is an inverse relationship between permeability rates and fine sediment storage; as fine sediment concentrations increase, permeability rates decrease.

By identifying and documenting areas of poor habitat quality, and by determining the likely cause of the degraded habitat, we can better guide future investigations (e.g., sediment source analysis to determine the origin of fine sediment) and suggest management interventions (e.g., more frequent high flow events to scour the bed and expose subsurface fines to transport, sediment control initiatives in targeted watersheds) to improve habitat quality.

Methods

At each sampling location, we will drive the permeability standpipe to a depth of six inches. Using the permeability backpack with sipping rod, we will collect multiple permeability measurements at this depth. For each trial, we will record the volume of water collected, the time required to collect the sample, and the clarity of the captured water sample. All measurements will be recorded in a waterproof field book or datasheet. In the same location, we will drive the standpipe to a depth of twelve inches and collect multiple permeability measurements, which will be recorded. For each set of multiple trials, the permeability rates will be averaged.
We will sample a minimum of ten sites, conducting multiple trials at depths of six inches and twelve inches.

Sampling Dates

Permeability sampling will be conducted in October and November, 2005, which is the period when flows typically recede as a function of reduced water supply deliveries and the expiration of seasonal water temperature management requirements. This sampling period generally occurs before winter rains that can cause increases in flow and turbidity that complicate field sampling. Sampling during autumn base flows will allow researchers to wade farther into the channel to collect samples in areas that are inundated perennially and more representative of salmonid spawning habitat, rather than being limited to the channel margins in zones that may be seasonally dry.

6.4 Scour Chains

Scour chains provide a method for estimating the flows required to mobilize and scour sediment stored in the channel bed. By burying chains vertically in the channel bed, we can monitor the depth of scour achieved by high flow events, which can be correlated with discharge data from the nearest flow gauge to develop coarse discharge-scour relationships. As scouring flows erode material surrounding the vertical scour chain, exposed links of the chain will change their orientation from vertical to horizontal at the level of the new bed surface. Excavating the scour chains following a high flow event provides an indication of the depth of scour as measured from the original bed surface.

Scour chains can also support an estimate of the amount of sediment that deposits on the recession limb of a high flow event, because we can measure the depth of sediment covering the scour chain from the new bed surface.

Sampling Area

We hypothesize that much of the channel bed between Keswick Dam (RM 302) and Cottonwood Creek (RM 273.5) has coarsened as a result of reduced sediment supply and continuing high flow events. Because Cottonwood Creek provides the first significant sediment supply to the mainstem channel, the potential for bed mobilization and scour is likely highest below the confluence, where the channel bed is likely to be composed of finer material. Consequently, we will focus scour chain placement below the confluence with Cottonwood Creek.

Scour chains will be placed in heavily used spawning areas, because discharge-scour relationships are useful for assessing the risk of redd scour associated with high flow events. In the Sacramento River, we estimate that Chinook salmon generally deposit eggs in pockets at depths ranging between six inches and 18 inches. Determining an estimate of the flow magnitudes that scour the channel bed to these depths in heavily used spawning areas can provide resource managers with a flow release guideline to manage redd scour during salmonid egg incubation periods.

Discharge-scour relationships can also provide guidelines for high flow releases designed to improve spawning habitat quality by mobilizing gravel and exposing subsurface fines to downstream transport, which can help prevent framework gravel from becoming cemented, and which may reduce the volume of fine sediment stored in the channel bed.[13] To achieve the desired benefits, the flow release would ideally re-work the gravel matrix to a depth where salmonids deposit eggs, though the flow release would be timed to avoid or minimize the effects of redd scour.

Methods

At each sampling site, field scientists will select an inundated area of the channel bed that is representative of the surrounding surface. Four scour chains will be planted in a square pattern, with a distance of 5 m separating each chain. Chains will be installed by enclosing each chain in a driving cylinder, which will be pounded into the bed to a depth of 18 inches. Once the targeted

[13] Flows capable of scouring the bed and exposing subsurface fines to downstream transport may not necessarily reduce the volume of fine sediment stored in the channel, which is also influenced by fine sediment loading.

depth is achieved, the cylinder will be removed from the channel bed, leaving the vertical scour chain buried in the surrounding matrix.

At each sampling site, field scientists will establish two resection lines to assist the process of re-locating the scour chains following a high flow event. The resection lines will intersect at one of the scour chains. Each resection line will be created by positioning two pins in alignment with one of the placed scour chains and driving the pins into the bed surface. By re-locating the pins, field scientists will reconstruct the resection lines following a high flow event to help identify the location of the scour chain located at the intersection of the resection lines.

We will place scour chains at a minimum of five sites.

Sampling Dates

Scour chains will be deployed in mid- to late-December, 2005, as long as flow conditions permit safe access to sample sites by boat. Because we will sample active spawning sites, the goal is to install the scour chains after the bulk of fall-run salmon spawning activity has occurred in order to avoid biological scour associated with redd construction. We will re-visit the sampling sites and exhume the scour chains following a high flow event of sufficient magnitude to induce bed scour.

6.5 Scour Boxes

Scour boxes provide a method for estimating the flow magnitudes required to mobilize the surface of the channel bed. A plot of exposed surface is covered with bright paint, and when the painted surface is mobilized by flows, the painted area becomes disrupted. Evidence of bed mobilization can then be correlated with discharge data from the nearest flow gauge to identify the flow magnitude that achieved bed mobilization. Relative to other methods for monitoring bed mobilization (e.g, tracers), scour boxes have the advantage of reducing disturbance of the sampled surface so that it remains representative of the surrounding area.
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Sampling Area

We hypothesize that much of the channel bed between Keswick Dam (RM 302) and Cottonwood Creek (RM 273.5) has coarsened as a result of reduced sediment supply and continuing high flow events. Because Cottonwood Creek provides the first significant sediment supply to the mainstem channel, the potential for bed mobilization and scour is likely highest below the confluence, where the channel bed is likely to be composed of finer material. Consequently, we will place scour boxes below the confluence with Cottonwood Creek. Scour boxes will be placed on dry, exposed bar surfaces so that paint will adhere to the bed surface.

Methods

At each sampling site, field scientists will select an area of an exposed bar surface that is representative of the surrounding bed surface. Using brightly colored spray-paint, we will paint three 5 ft by 5 ft boxes on exposed bar surfaces near the water's edge. Each scour box will be spaced 20 feet apart, starting at the head of the exposed point bar. We will place a minimum of five scour boxes. Field technicians will be careful to minimize disturbance of the sample site to reduce any changes in the degree of compaction of the bed surface.

We will monitor high flow events by tracking real-time discharge data for CDEC gauging stations. Following a potential bed mobilizing event, we will re-visit the sample sites to record evidence of mobilization of the sampled bed surface. If bed mobilization is documented, then we will retrieve discharge data from the nearest gauging station to identify the peak magnitude flow that occurred since the scour boxes were completed. Correlating this discharge event with evidence of bed surface mobilization will allow us to bracket the flow magnitude that initiates bed mobilization.

If a potential bed mobilizing flow occurs early in the high flow season so that we can re-visit the sample sites in early winter, then we will paint additional scour boxes at the sample sites during this re-visit to the sites. The additional scour boxes will allow us to record the effects of other high flow events that may occur later in the high flow season.

Sampling Dates

Scour boxes will be completed by mid-December, 2005 before winter high flow events typically occur. We will re-visit the sample sites once following a high flow event to determine if the sampled surface has been mobilized. Because the scour boxes are large enough to be seen from the air, we will communicate with CDFG personnel to ask for their assistance in monitoring the scour boxes as part of their aerial redd surveys for late-fall-run salmon, which are usually conducted once a month between December and March. Aerial monitoring of the scour boxes can help us ensure that a field visit will occur after we have evidence of a bed mobilizing event, thereby helping to prevent unproductive trips to the field to monitor the sample areas.

6.6 Map 2005 spawning habitat

The 1964 and 1980 surveys of spawning habitat provide a tool for assessing whether the channel bed below Keswick Dam has become more coarse. However, there have been significant flow events since the 1980 surveys were conducted, which we hypothesize have coarsened the bed further and caused bed coarsening to propagate downstream. The 1964 and 1980 surveys do not provide material to test the hypothesis that bed coarsening is continuing to propagate downstream, which requires a new survey.

We will re-survey spawning habitat using the similar methods applied in the 1964 and 1980 surveys—conducting aerial redd surveys to delineate spawning habitat that is based on actual salmon use of gravel. We will conduct the aerial redd survey during the fall of 2005, when fall-run Chinook salmon are spawning in the mainstem channel. Fall-run escapements are the highest of all the mainstem salmonid spawning populations; consequently, the fall-run salmon spawning should provide the best estimate of the maximum amount of spawning habitat currently available in the channel and, therefore, a more rigorous test of the bed coarsening hypothesis. After the aerial redd survey, the maps will be digitized in a GIS to support calculation of current spawning habitat and a comparison with the 1964 and 1980 surveys.

Resurveying of spawning habitat will also support an analysis of downstream propagation of bed coarsening, by seeing if cumulative spawning habitat has decreased farther downstream since the 1980 survey. This analysis has important implications for the fall-run Chinook salmon population. Though fall-run Chinook salmon abundance is the highest of the mainstem salmonid spawning populations (albeit much reduced from historical levels), this higher escapement may be because the fall-run has more spawning habitat available to them then the other salmon runs. Fall-run spawn at a time when suitable water temperatures stretch farther downstream than when winter-run and spring-run spawn. As a result, fall-run can take advantage of more cumulative spawning habitat in the river. However, if bed coarsening is propagating downstream, then the amount of spawning habitat available to fall-run may be declining.

Sampling Area

The spawning habitat survey will be conducted between Keswick Dam (RM 302) and Red Bluff Diversion Dam (RM 243). We hypothesize that bed coarsening has not propagated below the confluence with Cottonwood Creek, which is the first significant source of sediment supplied to the mainstem channel downstream of Keswick Dam. However, we will assess spawning habitat down to Red Bluff Diversion Dam in case bed coarsening has propagated farther downstream.

Methods

A broadcast quality video camera will be mounted to the nose of a helicopter to record videography of the channel bed. The camera will be connected to a digital video recorder and a GPS unit that will stamp the location of the helicopter on the recorded video. A field scientist will remotely control the video camera during the helicopter flight to cover the width of the channel and capture redd locations on video.

The recorded video will be digitized to facilitate analysis. Using the recorded video, we will identify redd locations and mark the corresponding locations of spawning habitat on recent aerial photographs of the Sacramento River. The mapped spawning areas will be digitized for incorporation in a GIS. We will use the GIS to calculate spawning habitat area by river mile and compare the results with the 1964 and 1980 surveys.

Sampling Dates

We will time the helicopter videography to coincide with the peak of fall-run spawning activity, sometime between late October and late November.[14] We will consult with agency personnel during the spawning season to track spawning activity and estimate the time of peak activity. By recording redd locations at the height of spawning for the salmonid run with the highest escapement numbers, we intend to capture spawning habitat when it is most likely to be saturated.

We will interpret the videography, map spawning habitat, digitize spawning habitat, and conduct habitat analysis between December, 2005 and May, 2006.

6.7 Facies mapping

Facies mapping involves delineating zones of homogeneous sediment, or facies, on a base map. Facies maps can provide a ground-check of the spawning habitat maps derived from the aerial redd surveys (Section 6.6). By comparing facies with the location of mapped spawning areas, we can assess the sediment sizes used by salmon in the Sacramento River and, in particular, look at areas that were formerly suitable in 1964 or 1980, but not used in 2005, to assess whether particle sizes are too large now. Facies maps also provide a tool for assessing flow-sediment dynamics for a broader span of channel than that provided by surface counts and bulk samples, which are usually limited to exposed point bars or shallow water areas. Visibility of the channel bed is the primary limitation on facies mapping, so a broader extent of channel can usually be surveyed as compared with other methods for characterizing the channel bed (e.g., bulk sampling).

[14] The timing of the helicopter videography will also depend on the availability of aircraft, weather conditions, and turbidity.

Sampling Area

Facies maps will be developed for five representative spawning locations in the study reach, between Keswick Dam (RM 302) and Colusa (RM 143).

Methods

Facies maps will be developed in the field by delineating zones of homogeneous sediment on recent color aerial photographs of the Sacramento River. We will map observable facies in shallow water areas that are accessible by wading, and we will conduct Wolman pebble counts to confirm the grain size classification of mapped facies.

Sampling Dates

One key use of the facies maps is to assess the influence of surface bed texture on the distribution of spawning as mapped by the survey described in Section 6.6. Consequently, facies mapping will be conducted after the spawning habitat maps are completed, in the spring of 2006.

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