FINAL REPORT:
Geomorphic Evaluation of Lower Clear Creek Downstream of Whiskeytown Dam, California

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1. INTRODUCTION

Restoration and management of regulated rivers is undergoing a fundamental shift in the underlying conceptual foundations (Anderson 1991, Williams et al. 1999, Nehlsen et al. 1991, NRC 1996, Stanford et al. 1996). This explicit set of principles and assumptions directs management activities, and defines the ways in which the natural and cultural attributes of a river system interact. Past and still widely entrenched management strategies on regulated rivers have generally relied on technological solutions and activities that either circumvent, replace, or grossly simplify the natural ecological attributes of river systems (NRC 1996; Stanford et al. 1996, Williams et al. 1999, McBain and Trush 2000). Examples of this technological reliance are: (1) exclusive use of the PHABSIM component of IFIM in setting minimum streamflow standards, (2) artificial propagation (hatcheries) in salmonid fisheries; and (3) large and expensive fish passage facilities at dams. This techno-emphasis combined with a general failure to incorporate a process-based emphasis in river management and restoration has contributed to the steady decline in river health, ecosystem function, and fishery populations. These past strategies no longer reflect the latest scientific understanding of ecosystem science and restoration. An alternative conceptual foundation based on restoring fluvial geomorphic processes as the foundation for ecosystem recovery is needed.

This emerging conceptual foundation for managing regulated rivers is derived from a synthesis of fluvial geomorphic and ecological principles, linked with the recognition that social-cultural institutions must be integrated with resource management (CALFED 1998, Stanford et al. 1996). This approach thus encompasses the entire natural-cultural landscape. The primary assumption of this approach is that physical (geomorphic) processes govern river ecosystems through their influence on the physical habitat structure and dynamics, and therefore an ecosystem-based approach must govern management and restoration decisions in order to reverse the consequences of land use on biological resources. As with any new approach, empirical data for gauging management decisions and actions are limited, and innovative decision-making must rely to a large extent on general principles. In this report we adopt a set of "Alluvial and Bedrock River Attributes" (Section 2.6.1) as quantifiable hypotheses of physical processes (theoretical assumptions) that can be used to guide the management and restoration of Clear Creek. This restoration approach is thus viewed as an hypothesis derived from the principles of river ecology (Stanford et al. 1996; McBain and Trush 2000).

The second basic assumption of the new conceptual foundation is that the river channel and associated floodplains, products of natural physical processes, provide the physical habitat upon which most riverine organisms depend for their existence. In other words, the product of physical processes acting on the landscape creates the unique set of conditions to which most native species, including anadromous salmonid species, have evolved. Thus, the most effective way to maintain the health and integrity of a river ecosystem and the dependent biological communities is by restoring and managing the fundamental physical processes. The link between physical and biological seems intuitive, but is challenging to demonstrate across the spectrum of ecological complexity.

The third fundamental assumption of this new approach, derived from its lack of thorough "field testing" asserts that present management *actions* must inform future management *decisions*. This concept is the basis for adaptive management (Holling 1978, Stanford et al. 1996, CALFED 1998, USFWS 1999), which is seen by many as an appropriate mechanism to ensure success in the face of scientific uncertainty (Lestelle et al. 1996). Conceptually simple: management/restoration as experiment, this approach becomes complicated to apply, given the diversity of stakeholder interests, lack of proven examples, inconsistent science, lack of external scientific review, and the immense variation in the degraded or altered conditions of regulated rivers. This administrative challenge is perhaps the most important aspect to successfully implementing any fundamentally new management approach. The Trinity River Adaptive

Environmental Assessment and Management program is the most developed adaptive management program in the region, and will be addressing many of the same restoration and management issues as will Clear Creek.

This report attempts to contribute to this new conceptual foundation and approach to restoration and management on Clear Creek by attempting to quantify thresholds and rates of sediment transport. Whiskeytown Dam has regulated Clear Creek, a tributary to the Sacramento River, since 1963, with most (63%) of its average annual runoff diverted from the reach downstream of Whiskeytown Dam. Flow and sediment regulation and other land use activities have damaged the channel and floodplains, and impaired salmonid populations. The 16 mile long river corridor below Whiskeytown Dam is relatively undeveloped and nearly entirely publicly owned (by BLM and NPS), provides a range of geomorphic conditions (steep bedrock canyons and lower gradient alluvial reaches), and historically supported several runs of Federally listed threatened or impaired anadromous salmonids, including fall, late fall, winter, and spring-run chinook salmon (*Oncorhynchus Tshawytscha*), and winter steelhead (*Oncorhynchus mykiss*). Perhaps most importantly for restoration purposes, high flow releases still occur and coarse sediment is available from locally abundant dredge-mining deposits.

2. HISTORICAL CONDITIONS

Clear Creek originates near 6,000 ft elevation in the Trinity Mountains, and flows south between the Trinity River basin to the west and the Sacramento River basin to the east, and into Whiskeytown Lake (Elevation 1,210 ft) at Oak Bottom, 11 miles west of Redding (Figure 1). The lower section of Clear Creek flows south from Whiskeytown Lake for approximately 8 miles, then flows east for 8 miles before joining the Sacramento River five miles south of Redding. The drainage area of Clear Creek upstream of the gaging station near Igo, CA is 228 mi^2, most of which is regulated by Whiskeytown Dam. This report focuses primarily on “lower Clear Creek”, the 17 mile long regulated section from Whiskeytown Dam downstream to the confluence with the Sacramento River.

Clear Creek is part of the Trinity River Division of the Central Valley Project, and Whiskeytown Dam has regulated streamflows since May 1963. Trans-basin diversions of streamflow from the Trinity River to the Sacramento River occur first through the 10.7 mile long Clear Creek Tunnel (and Judge Francis Carr Powerplant) into Whiskeytown Lake, and then through the Spring Creek Tunnel and Powerhouse into Keswick Reservoir on the Sacramento River, just north of Redding, CA (Figure 1). Whiskeytown Lake, formed by a 282 ft earthfill structure, has a storage capacity of 241,000 acre-ft. The entire volume of water diverted from the Trinity River basin and the majority of natural inflow into Whiskeytown Reservoir from the upper Clear Creek watershed are diverted through the Spring Creek tunnel into the Sacramento River to generate power. Only a small percentage of the annual runoff (~38%) is released into Clear Creek downstream of Whiskeytown Dam.

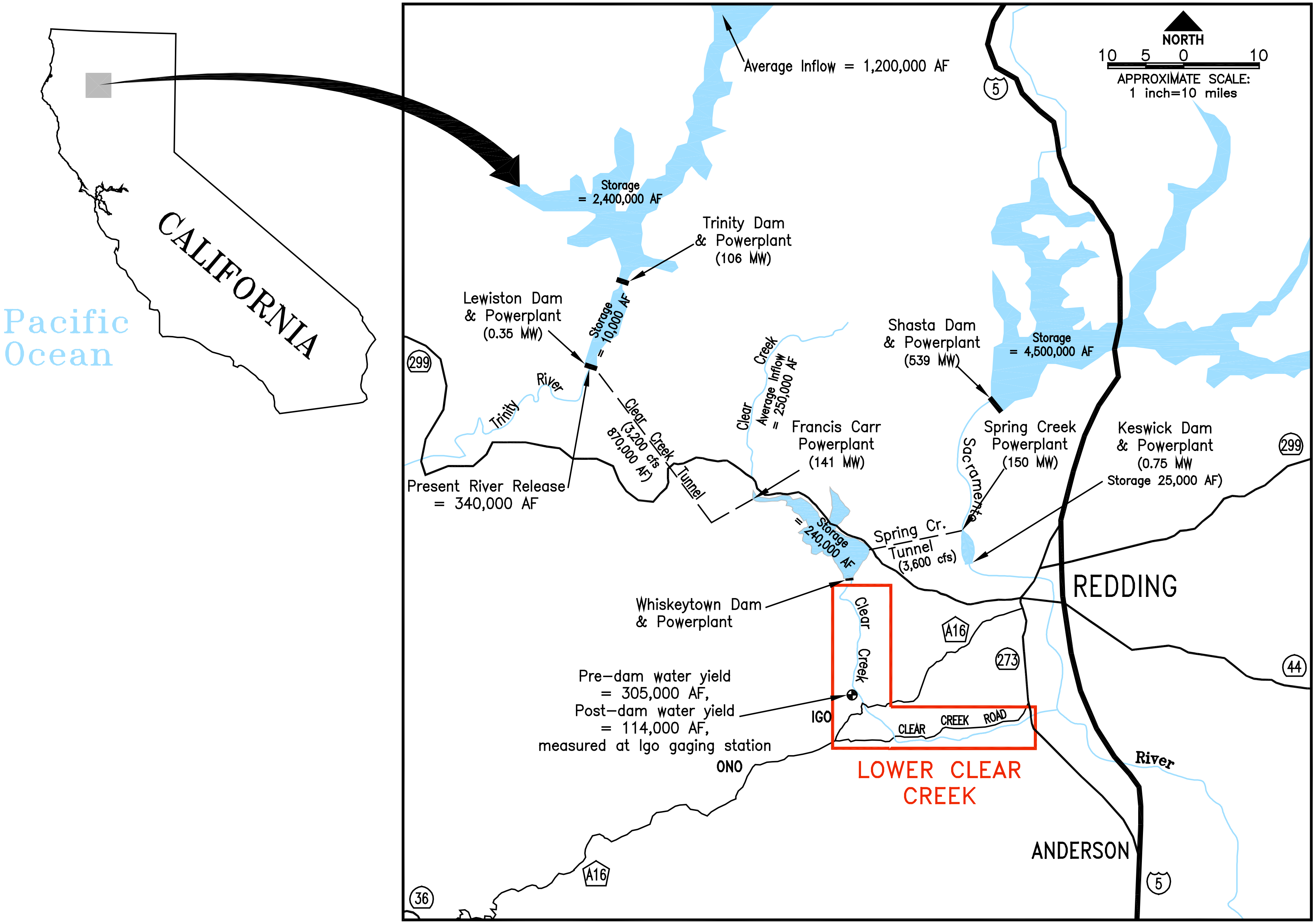
2.1. Geologic and Geomorphic Setting

The form and function of Clear Creek’s channel, and the biological communities inhabiting lower Clear Creek, are determined to a large extent by: 1) the geologic setting of the watershed (e.g., rock type, rates of erosion, uplift, or subsidence), and 2) the interaction of streamflow and sediment supply to the channel. This fact plays a large role in the morphology of lower Clear Creek, and defines unique geomorphic units.

Clear Creek flows through two distinct geologic provinces: the Klamath Mountains province and the Great Valley province (Blake et al., 1999). Most of the watershed lies within the Klamath Mountains province, which is composed primarily of Paleozoic to Mesozoic igneous, metasedimentary, and metamorphic lithologies. Lower sections of Clear Creek (below Whiskeytown Dam) lie primarily within the Great Valley province, which is composed of Mesozoic to Recent sedimentary lithologies. Both provinces not only provide different lithologic characteristics to Clear Creek alluvium, but also cause significant differences in channel morphology.

From Whiskeytown Dam to Clear Creek Bridge, the Clear Creek channel is predominantly bedrock-controlled, with tightly confined, steep canyon walls typical of streams within the Klamath Mountains province. The resulting channel morphology is a steep, confined bedrock stream with very little sediment storage. A notable exception to this general description is the two-mile long reach immediately downstream of Whiskeytown Dam, where the reduced bedrock confinement and gentler slope allow substantial gravel storage and alluvial channel features to develop.

The transition from the Klamath Mountains province to the Great Valley province occurs as Clear Creek exits the canyon at Clear Creek Bridge (RM 8.4) (Figure 2), with the Klamath Mountain province underlying the Great Valley province but becoming exposed briefly in the gorge below Saeltzer dam. The Great Valley province is younger in age and contains less resistant sediments (relative to lithologies of the Klamath Mountains province), which has allowed a wide alluvial valley to form within the canyon walls. Further downstream the river corridor continues to widen and eventually transitions into the Sacramento



Note:
Power Generation, storage capacity, and tunnel conveyance obtained from USBR Water and Power Resources Service Project Data handbook, 1981

FIGURE 1. CLEAR CREEK LOCATION MAP AND COMPONENTS OF THE SHASTA AND TRINITY DIVISONS OF THE CENTRAL VALLEY PROJECT

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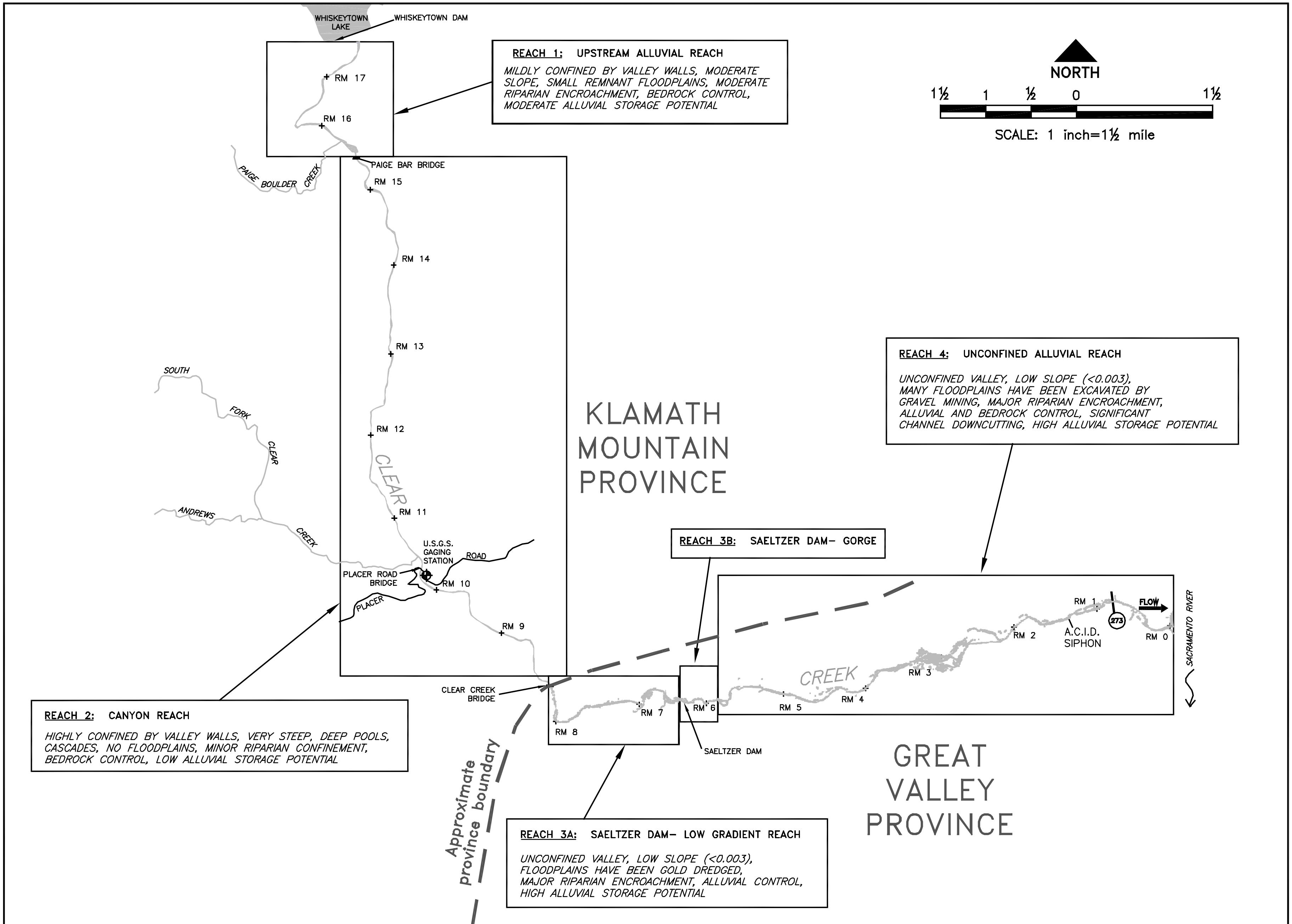

REACH 1: UPSTREAM ALLUVIAL REACH

MILDLY CONFINED BY VALLEY WALLS, MODERATE SLOPE, SMALL REMNANT FLOODPLAINS, MODERATE RIPARIAN ENCROACHMENT, BEDROCK CONTROL, MODERATE ALLUVIAL STORAGE POTENTIAL

REACH 2: CANYON REACH

HIGHLY CONFINED BY VALLEY WALLS, VERY STEEP, DEEP POOLS, CASCADES, NO FLOODPLAINS, MINOR RIPARIAN CONFINEMENT, BEDROCK CONTROL, LOW ALLUVIAL STORAGE POTENTIAL

REACH 3B: SAELTZER DAM– GORGE

REACH 3A: SAELTZER DAM– LOW GRADIENT REACH

UNCONFINED VALLEY, LOW SLOPE (<0.003), FLOODPLAINS HAVE BEEN GOLD DREDGED, MAJOR RIPARIAN ENCROACHMENT, ALLUVIAL CONTROL, HIGH ALLUVIAL STORAGE POTENTIAL

REACH 4: UNCONFINED ALLUVIAL REACH

UNCONFINED VALLEY, LOW SLOPE (<0.003), MANY FLOODPLAINS HAVE BEEN EXCAVATED BY GRAVEL MINING, MAJOR RIPARIAN ENCROACHMENT, ALLUVIAL AND BEDROCK CONTROL, SIGNIFICANT CHANNEL DOWNCUTTING, HIGH ALLUVIAL STORAGE POTENTIAL

FIGURE 2. LOWER CLEAR CREEK GEOMORPHIC REACHES, KLAMATH MOUNTAIN PROVINCE, AND GREAT VALLEY PROVINCE BOUNDARIES

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River valley. This lower section was historically semi-braided, meandering within the Clear Creek valley walls, with a floodway up to 1,000 ft wide. These geomorphic and geologic characteristics allow delineation of distinct reaches along Clear Creek, with fairly consistent channel and floodway morphologies.

2.1.1. Klamath Mountains Province

In the tightly confined channel type typical of the Klamath Mountains province, alluvial storage is minimal, with smaller alluvium typically depositing behind large boulders and bedrock outcroppings. These deposits have a high turnover rate, and supply is limited to coarse sediment delivered by tributaries and canyon walls. The notable exception to this general description is the short reach between Whiskeytown Dam and Paige Bar, where the corridor widens enough to allow gravel and cobble to deposit and form floodplains. These alluvial deposits still have a short residency time, but longer than in the canyon. These bedrock-dominated reaches usually do not have large volumes of alluvial storage due to the high energy present during floods. However, pre- and post-Whiskeytown Dam estimates of chinook spawning habitat, in conjunction with casual observations of canyon reaches upstream of Whiskeytown Dam, suggest that alluvial storage in the canyon reaches was much greater prior to the dam than at present.

The confined canyon has implications not only to alluvial storage, but also to fish habitat, migratory access, riparian vegetation, and sediment sources. Canyon reaches like these usually do not have large amounts of alluvial storage due to the high-energy environments during high flows. However, pre- and post-Whiskeytown Dam estimates of chinook spawning habitat (Coots, 1971), in conjunction with qualitative observations of alluvial storage in canyon reaches upstream of Whiskeytown Dam, suggest that alluvial storage was much greater prior to the dam than at present. Thus, spawning habitat available to spring-run chinook and steelhead below Whiskeytown Dam was likely more abundant than at present.

2.1.2. Great Valley Province

Clear Creek first encounters the Great Valley province downstream of Clear Creek Bridge. From the bridge downstream to below Saeltzer Dam, the Great Valley province shallowly overlies the Klamath Mountains province. The shallow bedrock of the Klamath Mountains Province transitions to a shallow clay hardpan of the Great Valley Province. Bedrock and clay hardpan remain shallow from the gorge to the Sacramento River confluence, with the exposed soft clay hardpan beginning just downstream of the gorge. Instream gravel extraction has increased clay hardpan exposure downstream of Saeltzer Dam, resulting in significant alteration to the natural channel morphology.

2.1.3. Summary

- Canyon walls and small tributaries in the Klamath Mountains province (Reach 1 and 2), and the remaining alluvial deposits in the creek itself, are now the primary sources of coarse sediment for lower Clear Creek.
- Confined canyon walls and steeper topography in the Klamath Mountains province cause channel morphology to be more confined, steeper, have less alluvial storage, and less riparian vegetation than reaches downstream of the Saeltzer Dam site. Bed substrate is predominately exposed bedrock, with patches of gravel and cobbles associated with boulders and bedrock outcroppings.
- Softer rocks and gentler topography of the reach in the Great Valley province results in a low gradient, less confined channel morphology in Reach 3A and Reach 4. Substrate is predominately cobbles and gravels, which provide high quality salmonid spawning and rearing habitats. Wide floodplains are allowed to form, which provides the space and finer sediments for more extensive riparian vegetation.

- Clear Creek used to be an important source of coarse sediment to the upper Sacramento River. Dams and gravel extraction on both the Sacramento River and Clear Creek greatly reduced coarse sediment supply, causing channel incision and bed coarsening in Reach 4 of Clear Creek.

2.2. Historical Land Use and Development

Clear Creek has undergone major changes as a result of natural resource development, beginning with gold mining in 1848. Discovery of gold at Reading Bar (RM 8.0) was second in California only to Sutter's Mill near Sacramento. Placer, hydraulic, and finally dredge mining literally transformed the natural landscape along the creek into barren piles of rock. In most locations, the deep alluvial deposits were "turned upside down", i.e., excavated, sifted to extract the gold, and then redeposited as dredger tailing piles on floodplains. In addition to the drastic physical alteration to the channel, gold mining also introduced temporary water storage and diversion operations to supply water during summer low-flow periods. Mining also brought secondary adverse impacts, including road building, deforestation, and urban development.

Streamflow hydrology was first modified during the gold rush (1848-1900) as water was diverted for placer mining. Early diversions were generally of small magnitude and consequently had little impact on the winter hydrograph, but probably diverted most of the summer baseflows. The impact of these diversions on channel morphology was minimal compared to the physical impacts of mining on channel morphology.

The next phase of hydrologic modification began in 1903, with completion of Saeltzer Dam at river mile 6.5. Saeltzer Dam served as the diversion point for 30 to 50 cfs delivered to farmlands and pastures on the north side of lower Clear Creek. Subsequent gold dredging and gravel mining of these pastures reduced the water demand over the years, so diversions from Saeltzer Dam were reduced to less than 10 cfs. The CALFED Bay Delta program funded removal of Saeltzer Dam in 2000, and the dam was removed in October 2000.

The largest changes in hydrology occurred after 1963, with construction of the Trinity River Division (TRD) of the Central Valley Project. The TRD was built and managed for hydropower production and to supply water for the Central Valley Project. Water from the Trinity River and most of the runoff from the upper Clear Creek watershed have been diverted via the Spring Creek tunnel from Whiskeytown reservoir into Keswick Reservoir on the Sacramento River (Figure 1). Whiskeytown Dam is an earthfill structure 282 feet high with a crest length of 4,000 ft., and with reservoir capacity of 241,000 acre-ft. Because power generation is a high priority, most water is sent from Whiskeytown Reservoir through Spring Creek tunnel to generate power. Flows are released into lower Clear Creek to provide minimum instream flows for fish. Large flood flows still periodically occur through the spillway. Average annual water yield into lower Clear Creek has been reduced 62%, from 302,000 acre-ft to 115,000 acre-ft. Flows released into lower Clear Creek join the Sacramento River approximately 16 miles downstream of Keswick Reservoir.

Whiskeytown Dam presently traps all coarse and fine sediment delivered from the upper watershed. This factor combined with the severely diminishes annual streamflow volume, annual flow variability, and high flow regime have collectively reduced the magnitude, duration, and frequency of critical fluvial processes. Alterations in the streamflow and sediment regimes have, in turn, brought ensuing changes in the downstream channel morphology and the distribution of riparian vegetation, and reductions in the quantity and quality of salmonid habitat and populations.

The last major impact to Clear Creek was commercial aggregate mining in the floodway in Reaches 3A and 4. Beginning in the 1950's, instream aggregate mining has degraded the channel and floodplains along lower Clear Creek. Beginning in the 1950's, several hundred thousand cubic yards of aggregate have been excavated from the floodway, destroying the bankfull channel confinement and entire floodplains, and creating in their place wide, shallow channels and interspersed abandoned mining pits. The channel, lacking confinement by alluvial banks, is no longer able to fully route sediment delivered to the reach, resulting in channel degradation over most of the reach. Excessive gravel extraction also exposed a clay hardpan throughout much of the channel bottom. Instream mining is no longer permitted and most commercial aggregate now comes from off-channel dredge tailings to the north of Clear Creek road. Off-channel gravel mining now targets old gold dredger tailings on the north side of Clear Creek Road (isolated from the stream), typically removing the tailings below the winter groundwater table.

2.3. Biological Resources

2.3.1. Anadromous Salmonids

Anadromous salmonids (salmon and steelhead) have existed on lower Clear Creek for millennia. Depending on the species, these fish used used various portions of the watershed, including reaches upstream of Whiskeytown Dam. Completion of Saeltzer Dam in 1903 and Whiskeytown Dam in 1964, combined with various land use activities in the watershed, has resulted in declines in most anadromous salmonids on lower Clear Creek.

2.3.1.1. Historical abundance and decline

Clear Creek historically supported four seasonal runs of anadromous salmonids, including fall, late-fall, and spring run chinook salmon (*Oncorhynchus tshawytscha*), and winter-run steelhead (*Oncorhynchus mykiss*). Life history adaptations and different spatial distributions allowed these runs to utilize the entire watershed to the fullest extent possible (Yoshiyama et al. 1998). Fall and late-fall chinook generally utilized mainstem habitats for spawning and rearing during fall through spring, while spring run chinook and steelhead historically accessed upper mainstem and tributary habitats during spring high flow runoff, held over during summer, and spawned in fall and winter. In addition to this seasonal variation in migration and spawning between different runs, variation also exists within each run, leading to considerable temporal overlap in life history stages between runs (USFWS 1995).

The long-term overall decline in abundance of anadromous salmonids was documented as early as 1929, and has received considerable attention recently (Nehlsen et al. 1991, NRC 1996, Yoshiyama et al. 1998). In Clear Creek, the major causes of decline were likely habitat destruction resulting from gold and aggregate mining, accumulation of fine sediment in spawning gravels, and further loss of habitat due to the construction of dams and water diversion projects. Because of differences in life history adaptations, each run has fared differently from the effects of streamflow regulation and habitat loss. Fall-run chinook abundance has fluctuated widely since 1951, from an estimated 10,000 adults in 1963 to fewer than 100 fish in 1978 (Table 1), but has generally been the most abundant run in Clear Creek (CALFED 1998). Three of the latest five years have exceeded the fall run chinook salmon escapement target of 7,100 adults set by the Anadromous Fish Restoration Program (USFWS 1995). Escapement estimates for late-fall run chinook are not available because they spawn in winter months when spawning surveys are more difficult due to periodic high flow conditions. Spring run chinook and steelhead have been impacted the most from water regulation and habitat loss; the spring-run population is nearly extinct, and both runs have been severely limited by lack of access to spawning and rearing habitats above the Saeltzer Dam site, and by high instream temperatures during summer. Removal of Saeltzer Dam in 2000 will greatly improve conditions for spring run chinook salmon and steelhead.

Table 1. Fall run chinook salmon escapement estimates for lower Clear Creek, 1951-1999.

Year	Fall-run chinook escapement
1951	700
1952	550
1953	1,500
1954	3,000
1955	500
1956	2,650
1957	330
1958	1,600
1959	755
1960	900
1962	5,400
1963	10,000
1964	2,500
1965	2,500
1966	900
1967	370
1968	800
1969	1,240
Missing data	
1976	1,013
1977	1,362
1978	60
1981	3,672
1982	785
1984	4,000
1985	700
1988	4,453
1989	2,154
1990	799
1991	2,027
1992	600
1993	1,246
1994	2,486
1995	9,298
1996	5,922
1997	8,569
1998	4,258*
1999	8,000

*Minimum estimate, first portion of run not counted

2.3.1.2. Recent restoration efforts

Efforts to improve anadromous salmonid populations have recently focused on lowering water temperatures and increasing habitat availability by increasing baseflows. Fish ladders were constructed to restore access upstream of Saeltzer Dam. In most years, fish ladders did not improve access upstream of Saeltzer Dam, so Saeltzer Dam was removed in October 2000. Attempts to reestablish spring run chinook have also included artificial supplementation. In 1991, 1992, and 1993, 200,000 juvenile spring chinook salmon from the Feather River hatchery were planted in Clear Creek (Brown 1996).

Habitat restoration efforts have also been initiated to reverse habitat degradation caused by gravel mining, gold dredging, and flow regulation. The primary habitat restoration project underway is the *Lower Clear Creek Floodway Rehabilitation Project*, which is designed to restore 1.7 miles of stream impacted by instream gravel mining and 0.5 miles of stream impacted by gold dredging. This project is designed to reconstruct a natural channel and floodplain morphology to (1) eliminate juvenile stranding mortality in off-channel mining pits, (2) improve adult migration through the mining reach, and (3) improve spawning and rearing habitat quantity and quality. Coarse sediment augmentation downstream of the Saeltzer Dam site has been conducted since 1996 to provide spawning gravel for spawning salmonids and to supplement the gravel mining reach restoration project (Table 2). Coarse sediment augmentation has also occurred immediately downstream of Whiskeytown Dam, and will now benefit steelhead and spring chinook salmon since access to this reach has been restored. The National Park Service, Bureau of Land Management, and Western Shasta Resource Conservation District are also implementing additional watershed rehabilitation efforts on lower Clear Creek.

Table 2. Spawning gravel introduction volumes and locations from 1996-2001 (from Western Shasta Resource Conservation District, 1997 and 2000).

Date	**Below Whiskeytown Dam (RM 17.5)**	**Igo Gaging Station (RM 10.0)**	**Below Saeltzer Dam (RM 6.1)**
June & December 1996	0 tons	0 tons	7,500 tons
September 1997	0 tons	0 tons	3,500 tons
January 1998	4,500 tons	0 tons	0 tons
December 1998	0 tons	0 tons	4,500 tons
July 1999	3,500 tons	0 tons	0 tons
October 1999	0 tons	0 tons	4,500 tons
July 2000	3,500 tons	0 tons	0 tons
December 2000	0 tons	3,000 tons	0 tons
February 2001	0 tons	3,000 tons	0 tons
May & June 2001	2,500 tons	0 tons	7,000 tons
Cumulative totals:	**14,000 tons**	**6,000 tons**	**27,000 tons**

2.3.2. Riparian Vegetation

This section provides a general description of riparian vegetation along the lower Clear Creek corridor, provides a list of key species along the corridor based on recent field surveys, and provides a brief illustration of relationships between riparian vegetation morphology and reach-scale channel morphology.

2.3.2.1. General Description

The distinct geomorphic zones along the Clear Creek floodway (Figure 2) provide a range of different geomorphic surfaces available for initiation and establishment by riparian vegetation. Along Clear Creek, riparian vegetation units were classified using the system of Sawyer and Keeler-Wolf (1995), which uses a *plant series classification* to describe both the dominant canopy species and subdominant understory vegetation. At least 20 different plant series have been identified within the lower alluvial reaches of the Clear Creek corridor (Bair 1999).

Historically, riparian vegetation in the canyon reaches (Reach 1 and 2) was likely sparse from a combination of scour during frequent high flows and lack of suitable growing areas in the confined canyon. Whikeytown Dam has reduced the high flow regime to the point where the plants are no longer scoured out as frequently so vegetation does grow from bedrock cracks, along small tributary deltas, and lee deposits. Arroyo and narrowleaf willows (*Salix lasiolepis* and *S. exigua*) thrive only where local site conditions can protect and sustain them. However, in several sections of Reach 1 (from Whiskeytown Dam to Paige Bar) where valley width is greater, white alder (*Alnus rhombifolia*) and Pacific willow (*S. lucida* ssp. *lasiandra*) have encroached along the low water channel in the absence of scouring floods, forming riparian berms along the low water channel. These berms contribute to channel bed degradation by confining high flows and increasing shear forces, and they may also reduce the extent and diversity of floodplain plant series by reducing or preventing inundation of floodplain surfaces.

In the alluvial reaches of Clear Creek, the riparian vegetation historically existed as a series of “stringers” or “patches”, usually correlated to abandoned primary channels or high flow scour channels where the water table was closer to the rooting surface. Clear Creek was gravel bedded, moderate gradient, semi-braided, and had no significant snowmelt hydrograph, so large expanses of riparian forest did not appear to exist. Subsequent episodes of land-use disturbance and flow regulation have greatly influenced the extent and species composition of riparian vegetation. A significant byproduct of dredge mining and aggregate mining was the wholesale removal of large floodplain areas and associated riparian vegetation. Dredger tailing surfaces are essentially deplete of soils, and only limited recolonization of dredged floodplains has occurred, mostly in the lower elevation depressions within dredger piles where tree roots can tap into buried soils and groundwater. Aggregate mining created shallow pits in former floodplain surfaces, which has allowed various wetland and riparian plant species to colonize the perennial and seasonal wetlands created by these mining pits. Wetland emergent vegetation has established in many of the ponds, and narrowleaf willow thickets and bands of white alder surround them.

In general, the alterations to channel morphology and high flow regime have created an environment more favorable to plants that seed in the summer (during low water), and for plants that develop a short-term seed bank, such as white alder. The attenuation of winter storm peaks has reduced the annual mortality of plants that seeded during summer months, leading to large stands of these species in areas where they were commonly scoured away before Whiskeytown Dam. Narrowleaf willow (a summer seeder) and white alder dominate vegetation on floodplains in alluvial reaches. Old Fremont Cottonwoods (*Populus fremontii*) (>50yrs) established in dredger tailing hollows, but little recruitment has occurred on the few remaining pre-dam floodplains. Cottonwood recruitment is now restricted to shallow surfaces adjacent to the active channel where gravel was once skimmed. These shallow ponds encourage deposition of fine sediment and are low enough to summer ground water levels to encourage recruitment. Additionally, the hot, dry climate and presence of dredger tailings has favored drought tolerant plants with long-lived seeds. Tree of heaven (*Ailanthus altissima*) and black locust (*Robinia psuedoacacia*) are common co-dominants in Fremont cottonwood or white alder series, while Himalaya berry (*Rubus discolor*) is a dominant understory plant in white alder series.

2.3.2.2. Sensitive Plant Species

Most of the Clear Creek corridor has not been surveyed for sensitive plant species. Bair (1999) conducted rare plant surveys at four sites in Reach 3A and 4 (325 acres total) in 1999. These field surveys covered all habitat types present on these sites that could support sensitive plant species: open river bars, seasonal wetlands, open water wetlands, relict valley oak stands, and contemporary cottonwood, alder, and willow stands. No rare, threatened, endangered, or candidate species, nor any California Native Plant Society List I or II plants were found.

2.3.2.3. Exotic Plant Species

During field surveys, approximately 230 plant taxa were observed in the Clear Creek riparian corridor (Bair 1999). Approximately 67% of the observed plant species are native species and 33% are non-native (exotic) species. Thirteen of the non-native species are classified as invasive exotics (i.e., non-native species with high potential to increase in abundance and replace native species). Himalaya berry, Tree of Heaven, black locust, and yellow star thistle (*Centaurea solstitialis*) are the primary invasive exotic species. Tamarisk (*Tamarix* sp.), white mulberry (*Morus alba*), and edible fig (*Ficus carica*) were also found, but observations suggest that these species are not yet proliferating. No giant reeds (*Arundo Donax*) were found in the riparian corridor.

2.3.2.4. Potential for Restoring Riparian Vegetation

The Lower Clear Creek corridor is one of few regulated rivers in California where the floodway is almost entirely publicly owned and undeveloped. The opportunity for restoration or rehabilitation of the riparian corridor is considerable, and could include:

- restoring and sustaining multi-age Fremont cottonwood and black willow stands, with diverse stand structures composes of arroyo willow on more dynamic alluvial deposits;
- riparian berm removal combined with channel rehabilitation to improve high flow access to floodplain surfaces, formation of alternate bar sequences, and aquatic habitat;
- high flow releases for channel and floodplain maintenance, to encourage floodplain development through fine sediment deposition, gap formations and natural recruitment;
- removal of exotic hardwood species (tree of heaven and black locust) to restore for restoration of a completely native riparian tree canopy to Central Valley riparian habitats.
- Periodic surveys for giant reed should be conducted, and removed if found in the Clear Creek riparian corridor.

2.3.3. Wildlife Resources

The lower Clear Creek watershed provides habitat for many wildlife species including various mammals, herpetofauna, and avifauna. Based on geographic and vegetative characteristics, the lower Clear Creek watershed is transitional between valley floor, foothill, and montane wildlife habitats. This transition is reflected by the wildlife species composition of the area, as a mixture of both resident and migratory valley and foothill/montane species occur. Wildlife inventories were conducted in lower Clear Creek in 1998 and 1999. Surveys observed the presence of four special-status wildlife species, little willow flycatcher (*Empidonax traillii brewsteri*), yellow-breasted chat (*Icteria virens*), yellow warbler (*Dendroica petechia)*, and northwestern pond turtle (*Clemmys marmorata marmorata*). Additionally, potential habitat for the federally threatened valley elderberry longhorn beetle (*Desmocerus californicus dimorphus*) (VELB) occurs within watershed and floodway. These special status species and other species of particular interest in Clear Creek include:

- Valley Elderberry Longhorn Beetle (*Desmocerus californicus dimorphus).*
- Bald Eagle (*Haliaeetus leucocephalus*).
- Bank Swallow *(Riparia riparia).*
- Little Willow Flycatcher (*Empidonax traillii brewsteri).*
- Yellow-Breasted Chat/Yellow Warbler (*Icteria virens*), (*Dendroica petechia).*
- Northwestern Pond Turtle (*Clemmys marmorata marmorata*).
- Foothill Yellow-Legged Frog (*Rana boyleii*).
- California Red-Legged Frog (*Rana aurora dratonii*).

2.4. Hydrology

The natural flow regime of a stream such as Clear Creek is an essential component in ecosystem health, structure, and function. Variability in flows is essential in sustaining the ecological *integrity* (e.g., long-term maintenance of biodiversity and productivity) and *resiliency* (e.g., capacity to endure natural and human disturbances) of the stream ecosystem (Stanford, et al. 1996). Fish communities, including anadromous salmonids, and riparian vegetation, were intimately adapted to inter-annual variation in streamflow (i.e., cycles of successive drought and wet years), and intra-annual variations (i.e., seasonal fluctuations in streamflow). For example, cottonwood seed availability was closely linked to the timing of spring peak runoff and recession, enabling seedling germination to occur on geomorphic surfaces that were low enough in elevation to access groundwater but high enough (relative to low flow channel) to reduce mortality from high flow scour.

Most hydrologic analyses tend to mask the true inter- and intra-annual streamflow variability by describing mean or median values (e.g., mean monthly hydrograph) or flow frequency statistics (e.g., exceedence flows). Our methods instead use water year classifications to characterize the inter-annual flow variability, and hydrograph components to describe intra-annual flow variability. In the following sections we present a water year analysis and hydrograph component analysis for pre- and post-regulated periods of record to evaluate the specific change in flow variability caused by regulation. We assume regulation from Whiskeytown Dam, completed in 1963, is the primary source of hydrologic alteration to the system.

Streamflow hydrology in lower Clear Creek is typical of streams draining the west side of the Sacramento Valley. Precipitation is primarily rainfall, with snow only occurring at the highest elevations of the watershed. Average annual precipitation in the Clear Creek watershed ranges from 20 inches near the confluence with the Sacramento River to over 60 inches in the upper watershed. The maximum watershed elevation is approximately 6,000 ft, but a majority of the watershed area is below the 4,000 ft snow line, so storm runoff is dominated by rainfall and rain-on-snow events. The 'Clear Creek near Igo' gaging station (USGS Station 11-372000), located 8 miles downstream of Whiskeytown Dam, has a drainage area of 228 mi^2, and is used in our analysis. Records exist for unimpaired water years 1941 to 1963, and regulated water years 1964 to present. Water year 1963 was regulated from May to September, but is included as unimpaired because diversions appear to be a small percentage of total annual yield.

2.4.1. Inter-annual Flow Variability

Streamflow is often described in terms of the average annual water yield (e.g., acre-ft per year). While this may be sufficient to describe a dependable long-term average water yield, averaging the long-term record masks the inter-annual variability that strongly influences river ecosystems. The water year classification method used here to describe inter-annual flow variability was originally developed for the Trinity River (McBain and Trush 1997) by plotting annual water yields as an exceedance probability. The distribution was then divided symmetrically into five equally weighted classes separated by annual exceedence probabilities (p) of 0.20, 0.40, 0.60, and 0.80 (Figure 3). Thus, five classes were developed and named “Extremely Wet” (p = 0 to 0.20), “Wet” (p = 0.20 to 0.40), “Normal” (p = 0.40 to 0.60), “Dry” (p = 0.60 to 0.80), and “Critically Dry” (p = 0.80 to 1.00). This classification system addresses the range of variability in annual yield and provides an equal probability for each class that a given water year will fall into that category (equally distributed around the mean), which in turn allows simpler comparisons between water year types. Other objectives (e.g., examining fall migration flows) require focusing on a specific portion of the year, and are discussed below as hydrograph components.

Evaluation of streamflow records for California rivers shows that wet years can have over 200% of the average annual yield, and drought years can have less than 30% (USFWS 1999, McBain and Trush 2000, CALFED 1998). Also, wet years and dry years often occur in clusters. During the last century, at least 5 clusters of wet years have occurred at about ten-year intervals, with intervening dry periods of similar duration. For example, the extended run of dry years from 1988 through 1994 was followed by five years of above average water yield from 1995 through 1999. Finally, the magnitude, timing, duration, and frequency of streamflow events can be significantly different among different water year types (Figure 4). For example, the snowmelt hydrograph may extend late into summer in wet years, but may be entirely

Figure 3. Probability distribution of PRE-DAM (unimpaired) water yield, split into 5 water year classes, for the Clear Creek near Igo gaging station

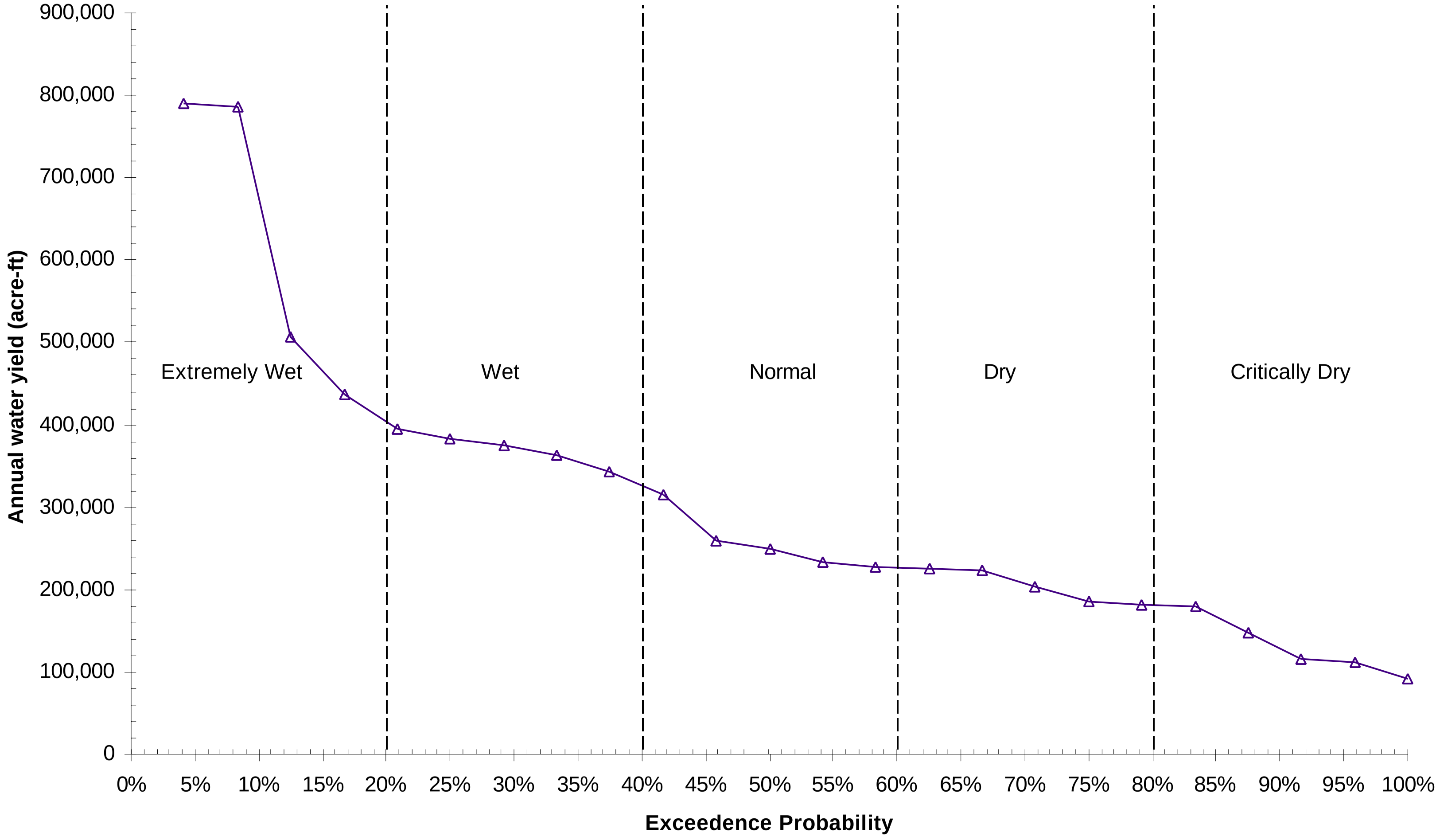
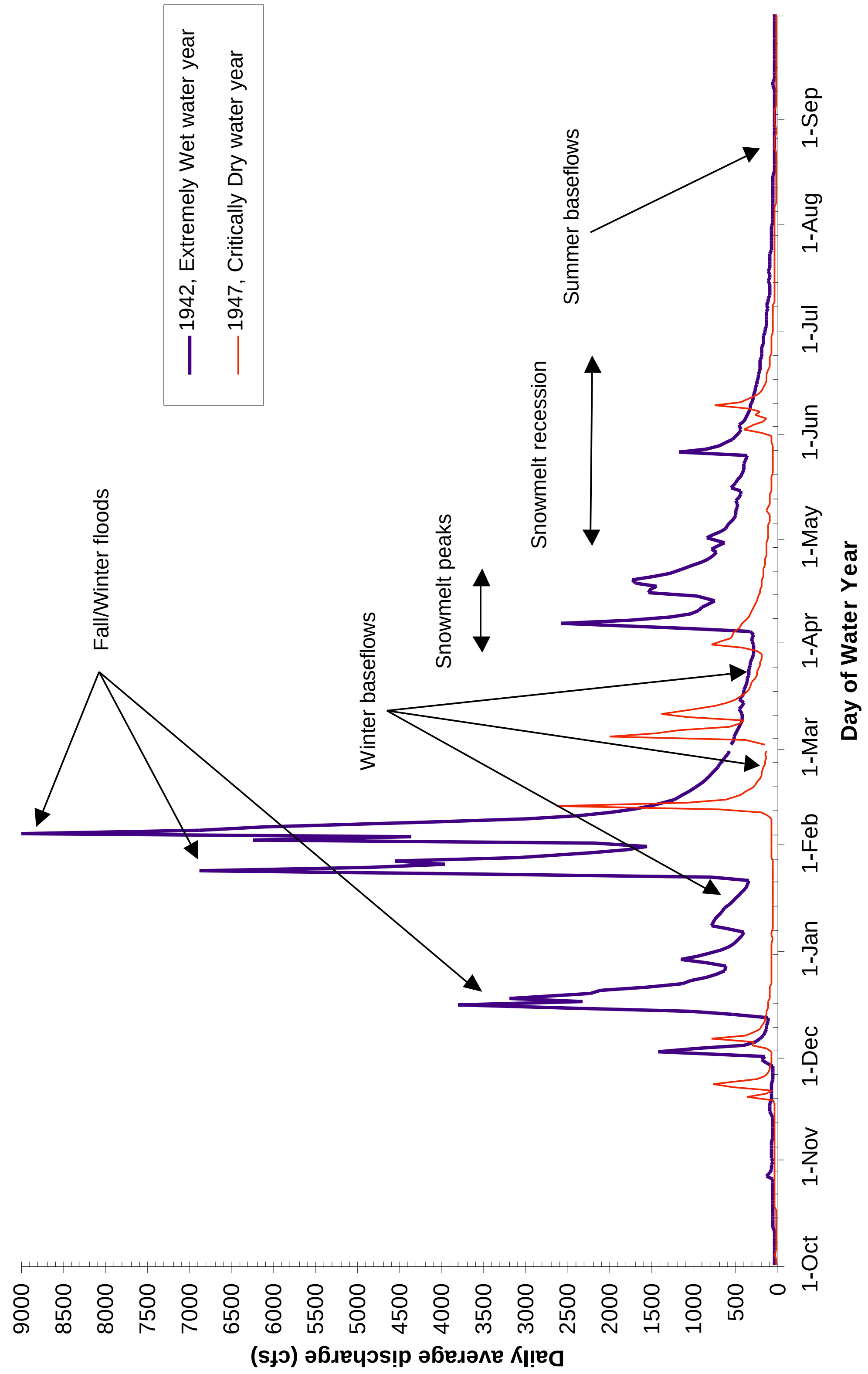


Figure 4. Representative Pre-Dam Extremely Wet and Critically Dry average annual hydrographs to illustrate differences in hydrograph components between water years



absent in dry years in some river systems. These differences among and within water year classes have meaningful geomorphic and biological consequences, as well as opportunities for Dam operations to achieve targeted flow releases, and must be considered in the recommendations for maintenance flows.

The average annual water yield in Clear Creek for unimpaired water years (WY 1941-63) was 302,000 acre-ft, and varied considerably from a low of 92,800 acre-ft (WY 1944) to 790,500 acre-ft (WY1941), nearly an order of magnitude difference in the natural inter-annual flow variability (Figure 5). Annual yield for the post-Whiskeytown period of record averaged 115,000 acre-ft, a 62% reduction from unimpaired conditions. Post-dam annual yields ranged from 41,800 acre-ft (WY 1977) to 412,600 acre-ft (WY 1983).

2.4.2. Intra-annual Flow Variability

As discussed earlier, the intra-annual flow regime is often described using average values, such as mean monthly flows. However, most geomorphic and ecological processes are dependent upon flows on a much smaller time scale, even as small as hours. Plotting daily average flows for each water year generates the average annual hydrograph (Figure 4), which generally provides enough detail to relate flows to geomorphic and ecological processes. A hydrograph component analysis of the unimpaired annual hydrographs is very useful to describe intra-annual flow variability (McBain and Trush 1997), and when overlain with the life-history of key biota, provides the foundation for hypotheses and conceptual models for how these species evolved and adapted to best survive under the unimpaired flow regime, and how changes to the unimpaired flow regime through watershed development (e.g., flow regulation, river engineering) has impacted these species. Clear Creek had five primary hydrograph components under unimpaired conditions: summer baseflows, fall/winter storms, winter baseflows, snowmelt peak, and snowmelt recession (Figure 4). Changes in streamflow volumes, magnitude, duration, frequency, and timing in lower Clear Creek have been dramatic, and have had significant impacts to fluvial processes, riparian dynamics, and salmonid life-histories. Overall changes can be summarized as follows:

- for most of the post-Whiskeytown Dam era, all hydrograph components except baseflows and infrequent fall/winter floods were eliminated,
- instream releases were between 40 and 50 cfs year round,
- any variability above the 40-50 cfs resulted from storm runoff from the watershed downstream of Whiskeytown Dam (approximately 50 mi^2) or uncontrolled spillway releases from Whiskeytown Dam.

These hydrograph components are described for both pre-Whiskeytown Dam (1941-1963) and post-Whiskeytown Dam (1964-present) periods.

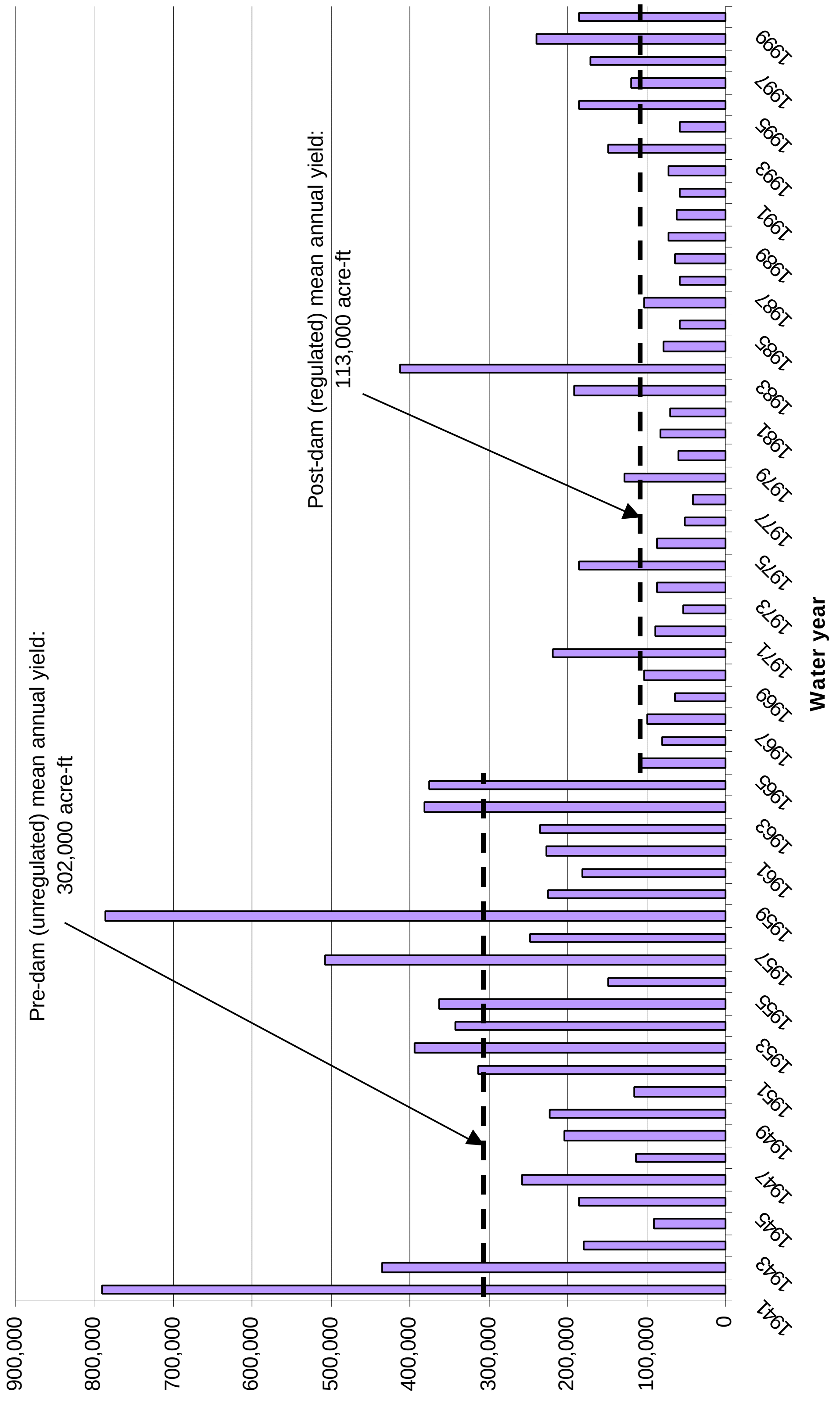
2.4.3. Hydrograph Components

The following hydrograph components evaluation compares differences between pre-dam water years (1941-1963) and post-dam water years (1964-1999).

2.4.3.1. Summer baseflows

Summer baseflows were very low, typically less than 60 cfs in the summer during wetter water years and less than 30 cfs in drier years (Figure 4). Summer baseflows began at the end of the snowmelt hydrograph in June/July, and ended in November/December with the arrival of the first rainfall events. The granitic and metamorphic rocks that comprise the upper Clear Creek watershed have low permeability, so winter precipitation runs off relatively rapidly, resulting in low summer baseflows. In contrast, streams draining the east side of the upper Sacramento Valley (e.g., Battle Creek) have fractured basalts that store precipitation for later release into the streams as large springs that provide high summer baseflows.

Figure 5. Pre-and Post-Whiskeytown Dam water yield histograms at the Clear Creek near Igo gaging station, 1941-1999



As is often the case with regulated rivers, the summer baseflows have actually increased due to regulation by Whiskeytown Dam. Pre-dam summer baseflows, typically between 20 and 60 cfs as measured at the Igo gaging station, were increased to 40 to 60 cfs for most of the post-Whiskeytown Dam era. In WY 1999, summer baseflows were increased to 150 cfs to provide cool water temperatures for juvenile steelhead and adult spring-run chinook salmon downstream of Saeltzer Dam. These flows will be reevaluated once the removal of Saeltzer Dam restores spring-run chinook and steelhead access to colder holding habitats upstream.

2.4.3.2. Fall and winter storms

Fall and winter storms were the dominant hydrologic and geomorphic event within lower Clear Creek. These storms typically occurred from November to March, with the largest storms occurring in January and February during rain-on-snow events (Figure 4). The low elevation and relative imperviousness of the watershed, combined with periodic high intensity rainstorms, resulted in an extremely flashy streamflow response to rainfall events. Floods were of large magnitude and short duration relative to the small watershed area, with instantaneous peaks sometimes greater than 20,000 cfs. Most geomorphic activity (channel migration, bedload transport, floodplain formation) occurred during these short duration storm events, with more avulsive geomorphic work resulting from large rain-on-snow events exceeding 20,000 cfs. These larger events caused the channel to avulse or migrate, scour and redeposit alluvial sediments, and erode patches of riparian vegetation. Generally, wetter water years produced larger peak flows than dry years. Dry water years typically had instantaneous peak floods between 3,000 cfs and 6,000 cfs, while wetter years had instantaneous peak floods between 10,000 cfs and 15,000 cfs. Fall and winter storms also provided discharge and temperature stimuli for fall-run chinook and steelhead upstream migration from the Sacramento River, and facilitated access to spawning grounds in higher elevation portions of the watershed.

Regulation from Whiskeytown Dam has greatly reduced the magnitude and frequency of high flows (Figure 6). The notable exception is large magnitude floods greater than 8,000 cfs, which fill Whiskeytown Reservoir and spill into the glory hole spillway. These large floods still occur because Whiskeytown Reservoir is not operated for flood control, and is thus maintained near maximum capacity. The “Glory Hole” spillway had the capacity to convey uncontrolled flows up to 23,000 cfs (maximum observed release is 19,200 cfs); however, the outlet works can only release a maximum flow of 1,200 cfs. Flood frequency analyses were performed for three data sets: annual instantaneous maximum series, one-day maximum daily average series, and three-day maximum daily average series. Annual maximum data was obtained from the USGS, and analyzed using the standard log-Pearson III flood frequency analysis (USGS, 1982). One-day and three-day data were obtained from USGS and analyzed by the NRCS using the same log-Pearson III analysis (NRCS, 1997). The annual maximum instantaneous series is shown in Figure 6, and results of all three analyses are summarized in Table 3, for unimpaired and regulated conditions.

The 1.5-year flood, often used as an indicator of a channel forming discharge, has been reduced from 5,700 cfs to 2,200 cfs. The magnitudes of 2.5, 5, and 10-year floods have also decreased significantly (Table 3). The unregulated watershed downstream of Whiskeytown Dam provides short duration peak floods, but the small, unregulated drainage area (<30 mi^2) prevents tributary floods from exceeding 3,000 cfs. The majority of post-dam floods are produced from tributaries downstream of Whiskeytown Dam, but floods larger than approximately 3,000 cfs generally result from uncontrolled spillway releases from Whiskeytown Dam, as happened during WY 1983 (19,200 cfs), 1997 (15,900 cfs) and 1998 (12,900 cfs). The unimpaired flood of record was 24,500 cfs in WY 1956 (December 21, 1955 flood). The largest flood of post-regulation period was 19,200 cfs in WY 1983. Unimpaired unit runoff for the 1.5-year flood was 24.7 cfs per mi^2, which Whiskeytown Dam reduced to 9.9 cfs per mi^2.

Figure 6. Pre-and Post-Whiskeytown Dam flood frequency curves at the Clear Creek near Igo gaging station (USGS stn 11-372000)

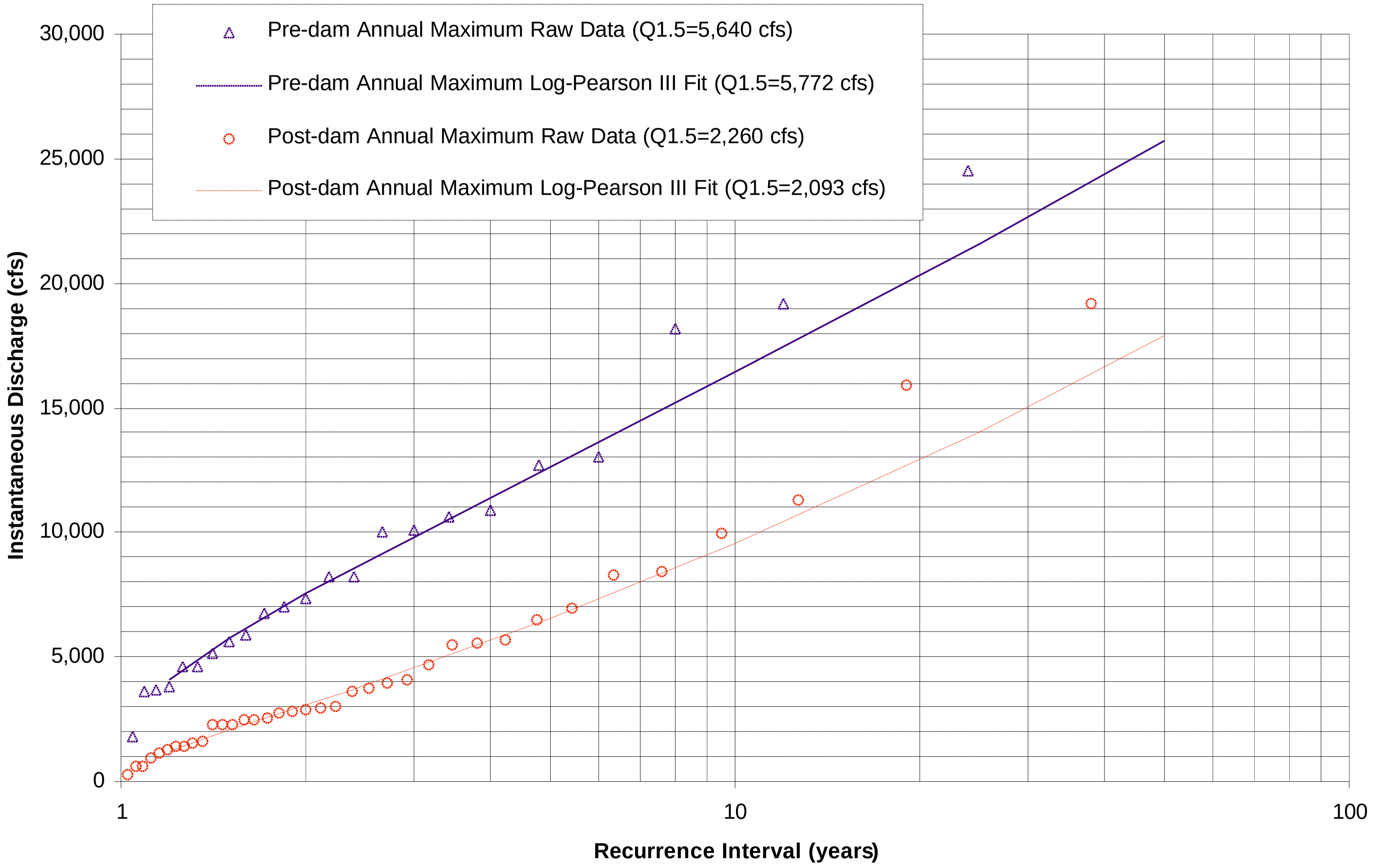


Table 3. Changes to Clear Creek near Igo gaging station flood magnitudes for 1.5 to 10 year floods.

	Annual instantaneous flood series			
	1.5 yr flood	2.5 yr flood	5 yr flood	10 yr flood
Unimpaired (WY1941-1963)	5,640	8,900	12,750	18,700
Regulated (WY 1964-2000)	2,067	3,750	6,550	9,530
Percent Reduction	63%	58%	49%	49%
	1-day daily average maximum flood series			
	1.5 yr flood	2.5 yr flood	5 yr flood	10 yr flood
Unimpaired (WY1941-1963)	3,690	6,185	9,048	14,300
Regulated (WY 1964-1997)	926	1,817	3,355	5,958
Percent Reduction	75%	71%	63%	58%
	3-day daily average maximum flood series			
	1.5 yr flood	2.5 yr flood	5 yr flood	10 yr flood
Unimpaired (WY1941-1963)	2,950	4,891	6,398	10,550
Regulated (WY 1964-1997)	648	1,253	2,336	4,380
Percent Reduction	78%	74%	63%	58%

Analysis of daily average flows, as opposed to the instantaneous maximum discharge, may be an important descriptor because the duration of the flow is longer than “instantaneous.” A one-day or three-day average may be a better measure for assessing impact to geomorphically important flows than the instantaneous peak values because the longer duration flows may be more indicative of geomorphic work achieved by the flow. We included a flow frequency analysis provided by NRCS (1997) for the 1-day average annual peak series and the 3-day average annual peak series (peak flow equaled or exceeded for 1 day or 3 consecutive days). Because of their sustained duration, these flows were reduced more by flow regulation than were the annual maximum floods, with reductions ranging between 58% and 78% (Table 3). The 1.5-year recurrence unimpaired 1-day average peak discharge decreased from 3,690 cfs to 926 cfs, and 1.5-year recurrence 3-day average unimpaired flow decreased from 2,950 cfs to 648 cfs.

2.4.3.3. *Winter baseflows*

Winter baseflows were moderate flows occurring between individual winter storm events, caused by the receding limb of winter storm hydrographs and contributions of groundwater drainage (Figure 4). These flows were geomorphically insignificant, but provided elevated flows for anadromous salmonid migration and spawning during the winter months. Winter baseflows generally occurred over the same period as fall/winter storm events, but often extended into the snowmelt hydrograph. Winter baseflows also varied by water year type, ranging between 100 cfs and 400 cfs during drier water years and 400 cfs to 900 cfs during wetter years.

The magnitude of typical winter baseflows was reduced by 50% or more after Whiskeytown Dam was completed, with reservoir releases typically set at 100 cfs between November 1 and January 1, then dropping to 40 to 60 cfs after January 1. The elevated 100 cfs baseflows from November 1 to January 1 are intended to provide attractant flows for adult fall-run chinook to migrate into Clear Creek from the Sacramento River, and to provide flows and temperature that maximize weighted usable area and suitable temperatures for fall-run chinook salmon spawning. Reclamation has recently increased winter baseflows from Whiskeytown Dam, up to 200 cfs in 1996/97 and 250 cfs in 1998. The watershed downstream of Whiskeytown Dam typically adds another 10 cfs to 30 cfs to winter baseflows measured at the USGS gaging station at Igo.

2.4.3.4. Snowmelt hydrograph

The historic snowmelt hydrograph on Clear Creek began in March or April, and often continued into July in wetter water years. The snowmelt hydrograph ended in late April or early June during drier water years. Compared to larger streams draining the Trinity and Sierra Nevada mountains, the unimpaired snowmelt hydrograph is small, with the snowmelt peak typically less than 1,000 cfs in drier years but occasionally exceeding 5,000 cfs in wetter years (Figure 4). These smaller magnitude flows were generally insufficient to accomplish meaningful geomorphic work, but were very important for providing access for spring-run chinook and steelhead to the upper watershed. The snowmelt hydrograph also wetted floodplain and scour channel surfaces during riparian seed dispersal periods, which encouraged successful riparian regeneration.

The small snowmelt hydrograph produced by the upper watershed has been completely absorbed by Whiskeytown Reservoir, and replaced by a continuous 50 to 100 cfs baseflow release from Whiskeytown Dam. A few small snowmelt hydrographs, most likely produced from Paige Boulder Creek and the South Fork Clear Creek, are observed in the post-Whiskeytown Dam hydrographs at the Igo gaging station, but they are nearly always less than 300 cfs.

2.4.4. Streamflow Management

Following construction of Whiskeytown Dam in 1963, the Bureau of Reclamation set minimum flow releases based on a tentative flow agreement between Reclamation, USFWS, and the National Park Service. The agreement called for the release of 50 cfs from January 1 to October 31, and 100 cfs for the remainder of the year during normal water years. Later, the USFWS recommended that flows increase to 250 cfs from May 15 to March 31 for normal water years, 225 cfs in April, and 150 cfs in May (Aceituno 1985). The Clear Creek Fishery Study (California Department of Water Resources 1986), which included input from the USFWS and CDFG, recommended that normal year flow releases be increased to 200 cfs from October 16 to March 31, and 150 cfs from April 1 to October 15. In addition, the study recommended incorporating adult attraction flows of 500 cfs from November through January to improve spawning habitat for salmon and steelhead, which would also improve water temperatures and rearing habitat for juvenile steelhead.

These baseflow recommendations are generally based on PHABSIM and temperature models that attempt to maximize the weighted usable area (WUA) and provide suitable temperature for anadromous salmonids. PHABSIM models do not consider high flows that are essential for creating and maintaining the quality of the available habitat. High flows for channel maintenance and sediment transport were not incorporated into the above recommendations

2.5. Fluvial Geomorphology

The natural characteristics of a river ecosystem are created and maintained by geomorphic and hydrologic processes that result from energy and material interactions between flowing water and sediment supply, and from secondary influences of riparian vegetation. Clear Creek, like many rivers in the Central Valley, exhibits a dynamic gradient of habitat types from headwaters to confluence. Salmonids, their habitats, and other aquatic flora and fauna are distributed in relatively predictable ways along that gradient, according to their specific life history requirements. Hence, describing the historic and contemporary fluvial geomorphic processes is important for assessing related ecological impacts.

Describing historic fluvial geomorphic conditions in Clear Creek is challenging because of the general lack of detailed data and observations describing “pre-disturbed” channel and floodplain conditions. In the absence of historical data specific to Clear Creek, we can surmise from general river ecosystem principles what the natural or historical conditions were in Clear Creek. Using an historical perspective allows us to begin to understand the direct and indirect adverse impacts that the dams and other land-use practices have had over the years, which can in turn aid in guiding future restoration actions to reverse these effects.

The following sections describes the general fluvial processes that form and maintain alluvial rivers, focusing on the lower Clear Creek reaches from Whiskeytown Dam (RM 17.5) to the Sacramento River (RM 0.0). We describe four distinct geomorphic reaches in lower Clear Creek, focusing on those geomorphic traits that will help form an understanding of historical conditions and aid in comparing to contemporary conditions. Last, this section summarizes the limited, but useful, historical information regarding Clear Creek's geomorphology.

2.5.1. Clear Creek Alluvial Reaches

Most of the following description applies to the alluvial reaches downstream of Clear Creek bridge (RM 8.4) for two primary reasons: (1) more is known about the general fluvial processes within alluvial rivers than bedrock rivers (Wohl, 2000), and (2) alluvial channels are more prone to impacts from land-use practices than are bedrock-controlled channel reaches.

2.5.1.1. Sediment supply and transport

Sediment is supplied to rivers as a result of erosional processes in headwater streams and tributaries. Typically, mass wasting and overland flow (sheetwash) processes are the largest contributors of eroded sediments into the stream channel. Because the upper Clear Creek watershed lies within the Klamath Mountains geologic province, moderate-to-low volumes of sediment are supplied to the channel (USGS 1972). Construction of Whiskeytown Dam in 1963 completely blocked the upstream supply of sediment to the reaches below the dam. Downstream of Whiskeytown Dam, only a few relatively small tributaries, such as Paige-Boulder Creek and the South Fork Clear Creek, provide a sediment source to lower Clear Creek (Figure 7). The bed and banks of alluvial rivers can also supply the channel with sediment. This process is particularly important in situations where upstream sediment supply is reduced or eliminated.

In general, alluvial channels are maintained in a "dynamic quasi-equilibrium" by transporting sediment load downstream at a rate approximately equal to the sediment supply (Schumm 1977). This process maintains the channel in a generally constant form, or morphology, over time, despite the continual routing of material through the system that produces local variations (complexity) in the channel bed topography. Sediment moving through the system is stored in depositional features such as gravel and cobble point bars, or on floodplains and terraces, and becomes mobilized and routed downstream during high flow events. During such high flows, particles from the surface of the channel bed are constantly being traded for new particles arriving from upstream. Therefore, the channel form remains relatively constant as sediment passes through the system.

Sediment is a general term that describes the solid rock and soil material that passes through the system. The term bedload applies to the sediment size fraction that moves on or near the bed, in contrast to the suspended load, which is transported in the water column. Channel bed "scour" and "fill" describe bed erosion and redeposition during relatively short periods of time. The channelbed tends to scour during high flows due to the increase in velocity and shear stress (force per unit area) on the bed. Conversely, as the shear force decreases with the fall in stage, sediment arriving from upstream tends to deposit on the bed, and the bed "fills" when there is adequate sediment supply. Scour and fill are beneficial processes that maintain channel morphology, prevent riparian encroachment into the active channel, and maintain aquatic habitat, including clean spawning gravels for salmonids.

In contrast, channel aggradation and degradation describe similar processes that occur over a longer time period, or when an imbalance occurs in sediment supply and transport (Leopold et al. 1964). Aggradation and degradation frequently have detrimental impacts on the river channel and ecosystem. For example,

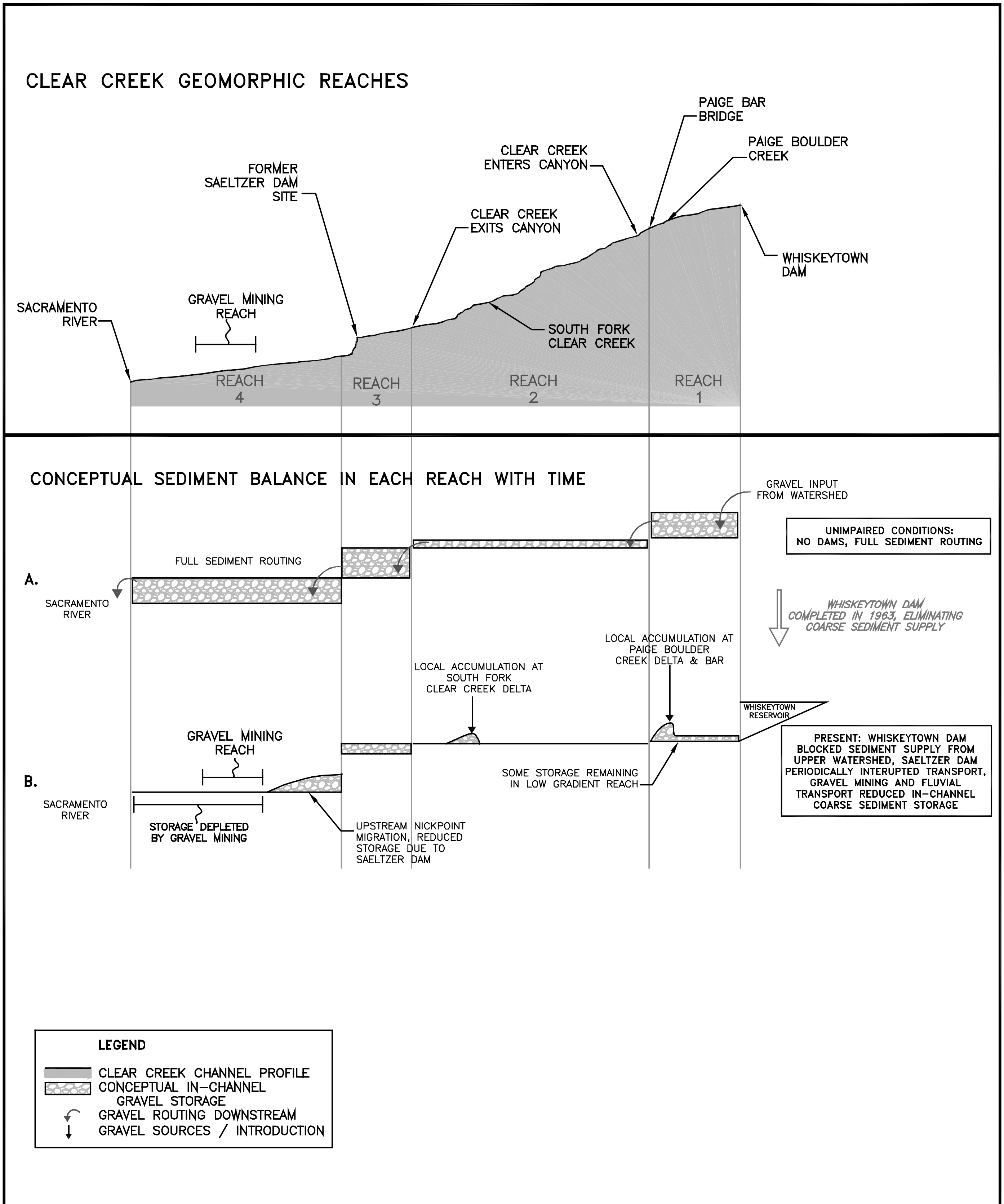


FIGURE 7. LOWER CLEAR CREEK
CONCEPTUAL MODEL OF HISTORICAL AND EXISTING
COARSE SEDIMENT STORAGE CONDITIONS

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many regulated rivers receive elevated rates of fine sediment (silt and sand) delivery to the channel, and combined with a reduced magnitude and frequency of floods, fine sediments accumulate in the channelbed, filling interstitial spaces among larger gravel and cobble particles. This process of bed "armoring" renders the channelbed more resistant to mobilization, reduces invertebrate production, and impairs the quality of salmonid spawning gravels.

Commercial aggregate mining in low-gradient alluvial reaches downstream of Saeltzer Dam resulted in the removal of hundreds of thousands of cubic yards of gravel from the floodway from 1950 to 1978. Small berms intended to isolate the stream from the mining pits failed, destroying the natural channel form and converting much of the channel bottom from gravels and cobbles to exposed clay hardpan. Comparison of the 1934 and 1997 water surface profiles has shown that bed elevations in the mining reaches have been lowered by 3 to 7 feet or more as a result of instream gravel mining and reduced coarse sediment supply. The Floodway Rehabilitation Project, initiated in 1999, seeks to reverse this impact by refilling the floodway with gravel to rebuild the bankfull channel and floodplain morphology.

2.5.1.2. Channel migration and avulsion

The channelbed and banks within the bankfull channel are relatively dynamic features, subject to frequent (e.g., annual) physical disturbance. On a longer temporal scale, the river planform is also dynamic, controlled by similar processes of scour and fill, and bank erosion and deposition. Channel migration and channel avulsion describe processes that change the planform location of a river channel. In general, channels formed in alluvium move laterally (migrate) by eroding the banks on the outside of a meander bend and concurrently depositing material (transported from upstream) on the inside of the meander bend. This imbalance between erosion and deposition is the driving force behind lateral migration (Figure 8).

Over time, the channel migrates across the entire valley floor, depositing fresh floodplains in its wake. Therefore, the flat floor of a valley is constructed by lateral migration and the deposition of sediment (Dunne and Leopold, 1978). As channels migrate laterally, they erode their own floodplain and terrace deposits. Generally, the eroded bank material is similar in composition to the contemporary bed material. In addition, migrating channels frequently erode into mature floodplain vegetation, toppling trees and dense shrubby vegetation into the channel.

Two forms of channel avulsion, or catastrophic relocation of the channel planform, are common to alluvial channels. In the first, lateral migration of the channel over time tends to increase the sinuosity and reduce the channel slope. As the channel becomes increasingly more sinuous, convergent points of meander bends come increasingly close together, to a point where the meander bend pinches off, usually during a high flow event. The meander cut-off forms oxbow lakes and sloughs, rich and productive habitat for establishment of riparian vegetation, and the channel migration process begins again. The second type of avulsion typically occurs in steeper semi-braided streams like Reaches 3A and 4 in Clear Creek, and tends to have a rapid relocation of the channel during a very large flood (e.g., 10 to 50 year flood). This type of channel avulsion was the dominant process maintaining the mixed age-class composition of riparian vegetation seen on pre-dam Clear Creek floodplains, and tended to result in intermittent patches and long rows of riparian vegetation in high-flow scour channels and abandoned low-flow channels.

Since construction of Whiskeytown Dam and the resultant reduction in flood flows, most channel migration and avulsion processes have been eliminated. Even though large floods still occasionally occur, the reduced frequency of floods has allowed riparian vegetation to establish and mature along the low-flow channel margins. This process of riparian encroachment effectively anchors or "fossilizes" the channel banks, rendering them more resistant to flood scour, and prevents channel migration. Riparian vegetation established along low-flow channel margins also encourages sand and silt deposition, which

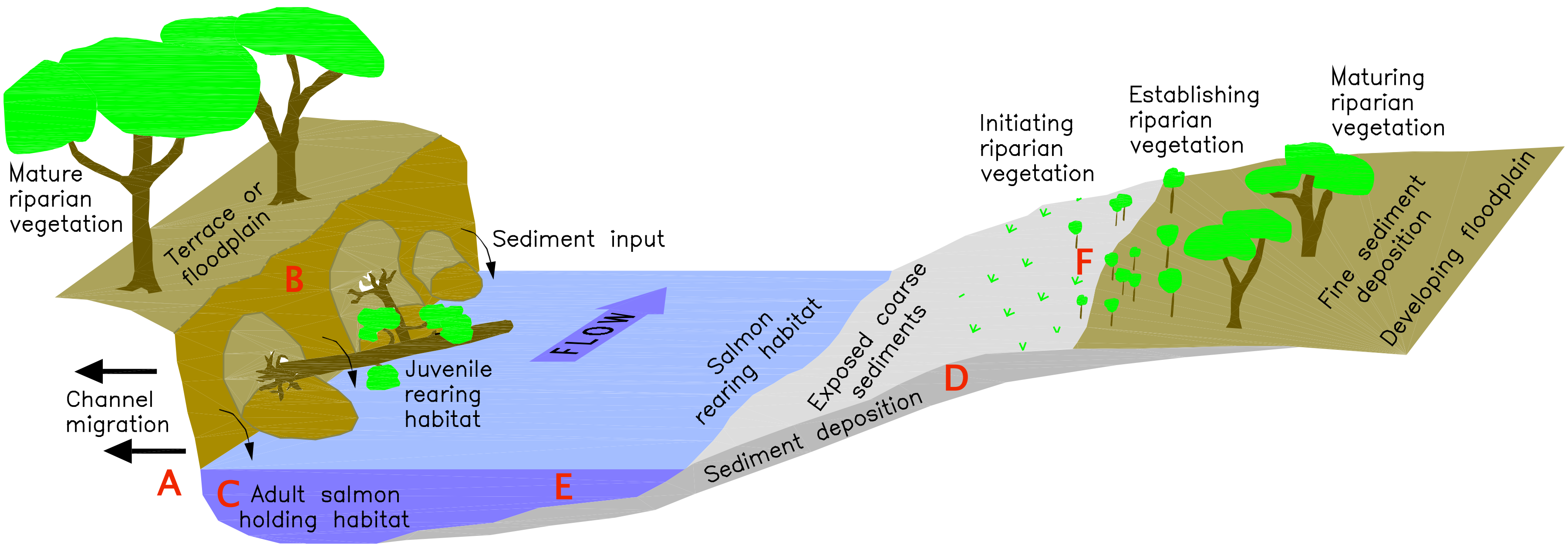

FIGURE 8. CONCEPTUAL MODEL OF CHANNEL MIGRATION, BAR FORMATION, FLOODPLAIN FORMATION, AND RELATION TO SALMONID HABITAT. (A) A channel with adequate space to migrate erodes the channel bank on the outside of the meander bend during high flows, (B) encouraging aged riparian trees to topple into the channel. (C) A deep pool also forms here, which provides structural complexity for good fish habitat. As bank erosion continues, the pool "migrates" with the channel, but high quality habitat is maintained. (D) On the opposite bank, high flows scour and redeposit coarse sediments, forming a point bar on the inside of the meander bend, and providing clean gravels for spawning and/or rearing. (E) This area, in turn, provides ideal slow–water rearing conditions for juvenile chinook salmon, as well as habitat for aquatic insects (fish food), amphibians and reptiles. (F) Progressively higher up the gravel bar surface, a dynamic interplay occurs between receding water levels during the spring snowmelt, and the presence of riparian tree seeds. These woody riparian trees are sporadically scoured out, and those established high enough on the bank are toppled into the channel as the channel migrates back across the valley (A).

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leads to the formation of riparian berms. These berms provide flow-resistant confinement of the low-flow channel, which in turn increases shear stress and bed degradation during subsequent flood flows.

2.5.1.3. Channel morphology

In most alluvial rivers similar to Clear Creek, there is a commonly used portion of the channel (the bankfull channel) and lateral floodplains. As flow increases in the channel, bedload transport initiates at discharges slightly less than bankfull discharge (the discharge in which flow begins to spill onto the floodplain). With continuing increase in discharge to the bankfull stage, bedload transport increases rapidly. With even more increase in discharge, the flow spills out onto the floodplain. When this occurs, water velocities slow, and reduce the rate of increase in shear stress and sediment transport (Figure 9). Although the rate of increase in shear stress is reduced, the bedload transport rate still continues to rise with increase in stage/discharge as lateral channel features (such as point bars) are mobilized.

This two-stage channel relationship (bankfull channel and floodplain) is critically important to allow scour and deposition of the channel while maintaining the channel's morphology. The erosion rate, sediment transport rate, and bar building by deposition are most active when the discharge is near bankfull. Although the highest discharges carry the most sediment during their passage, they are so infrequent that over time they do not accomplish as much work as the more frequent events (Leopold, 1994). Thus, the bankfull discharge transports a large portion of the total sediment load, and is important in scaling and maintaining the channel width, depth, velocity, meander wavelength, particle sizes, and other morphological features.

Within the bankfull channel of alluvial rivers, the prevalent morphological feature is the alternate bar sequence. An alternate bar sequence consists of two aggradational lobes or point bars, opposite and longitudinally offset from one another, and connected by a transverse bar (Figure 10). The point bars are located adjacent the deep scour pool on the outside of the meander bend, and water flowing across the transverse bar forms a riffle, hence the traditional pool-riffle sequence. On a broader scale, two alternate bars form a complete channel meander with a wavelength roughly equaling 9 to 11 bankfull channel widths (Leopold et al. 1964).

During low flows, the channel meanders though the alternating point bars, but during high flows the bars become submerged and the flow pattern straightens. During these periods of high energy, bedload is transported primarily across the face of these alternating point bars rather than along the thalweg (the deepest portion of channel). In unregulated healthy alluvial rivers, alternate bar surfaces are frequently mobilized, but overall bar morphology is retained between floods. This attests to the channel form remaining relatively constant as sediment passes through the system.

The topographic diversity provided by an alternate bar sequence is extremely important to aquatic organisms, particularly as habitat for anadromous salmonids. For example, at typical baseflows, an alternate bar sequence provides adult holding areas, preferred spawning substrates, early-emergence slack water, and winter/summer juvenile rearing habitats (Figure 10). In the initial stages of flow increases (above baseflows) the different micro-habitats remain available but in differing proportions and locations. Suitable spawning habitat in pool tails migrates downstream deeper into the riffle and laterally up the bar face as flow stage increases. Similarly, juvenile rearing habitat along the shallow margins of point bars also migrates laterally onto the bar surface, then onto the floodplain. The floodplain thus provides refugia (and high quality food resources) for juvenile salmonids during high flow events. Dams tend to reduce or eliminate the alternate bar morphology by allowing riparian vegetation encroachment and berm formation, followed by increased scour and downcutting of the channelbed, until finally the flow access to floodplains is eliminated except during extremely large flood events.

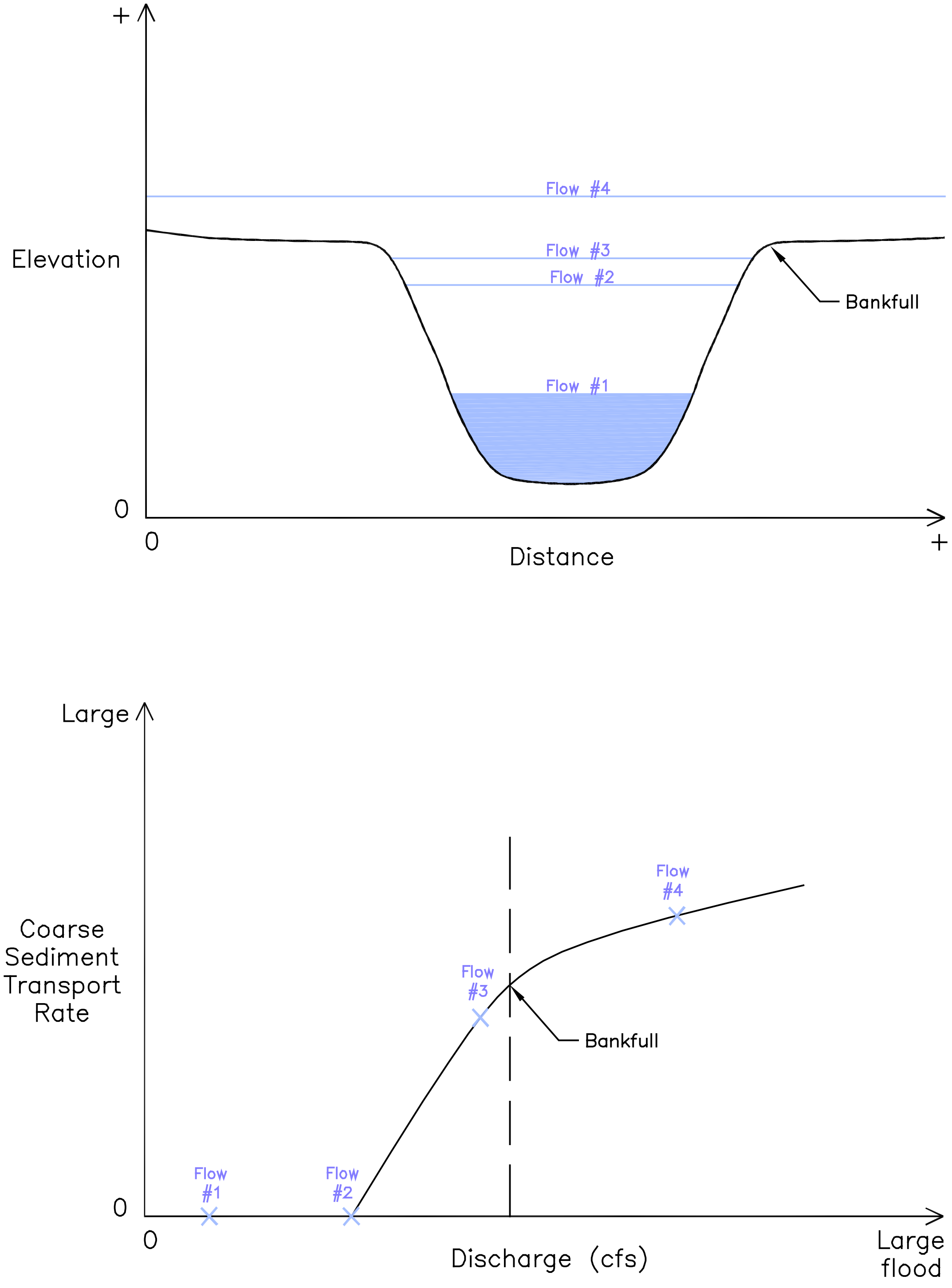

FIGURE 9. CONCEPTUAL RELATIONSHIP BETWEEN TWO STAGE CHANNEL AND COARSE SEDIMENT TRANSPORT RATES.
COARSE SEDIMENT TRANSPORT BEGINS AT A FLOW SLIGHTLY LESS THAN BANKFULL, INCREASES STEEPLY UP TO BANKFULL, THEN INCREASES AT A MORE GRADUAL RATE AT FLOWS GREATER THAN BANKFULL.

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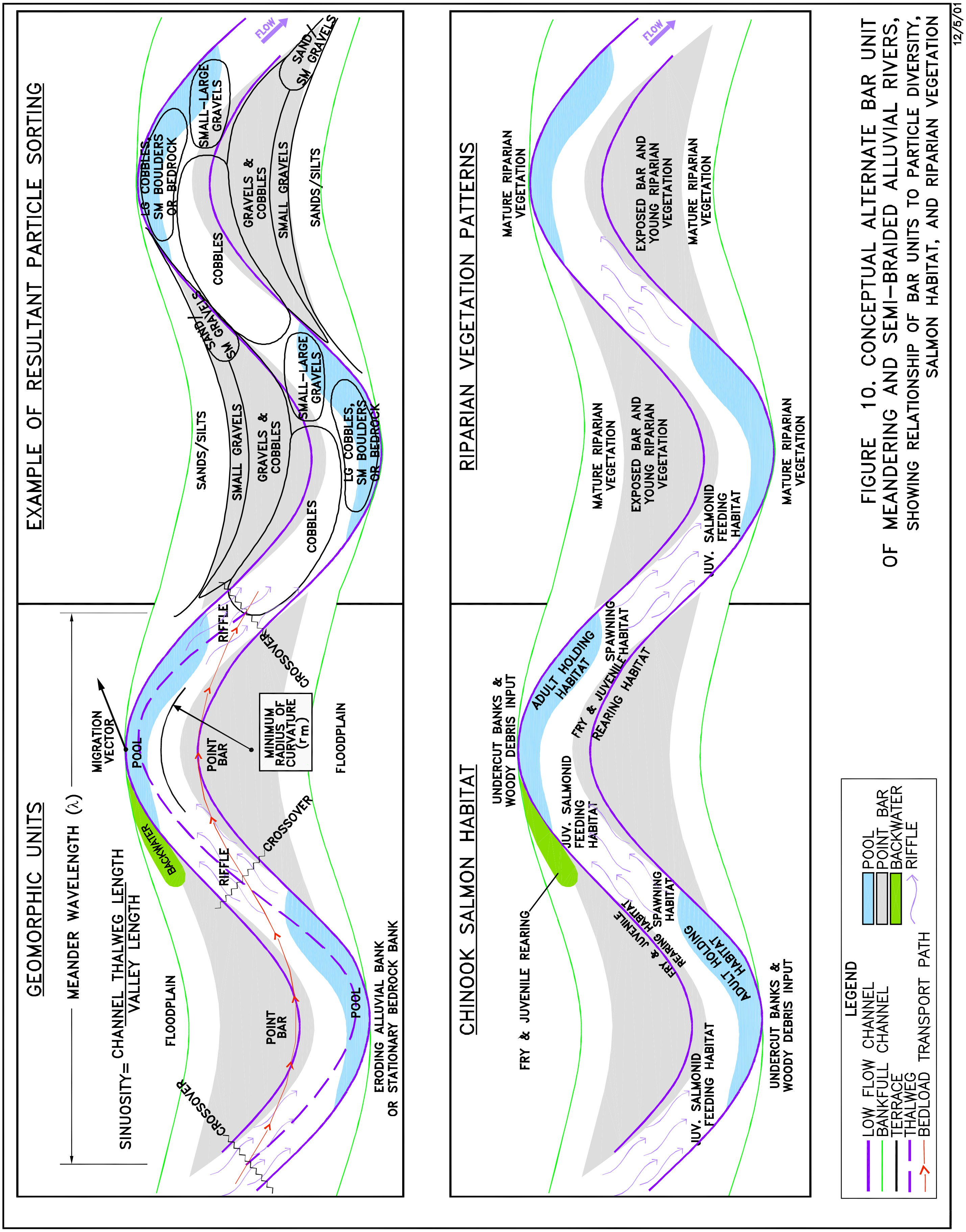

FIGURE 10. CONCEPTUAL ALTERNATE BAR UNIT OF MEANDERING AND SEMI-BRAIDED ALLUVIAL RIVERS, SHOWING RELATIONSHIP OF BAR UNITS TO PARTICLE DIVERSITY, SALMON HABITAT, AND RIPARIAN VEGETATION

In the alluvial reaches downstream of the Clear Creek Bridge, much more variation in morphology probably existed historically. Gold mining severely disturbed the channel before natural morphological conditions were documented. We have thus inferred historical (undisturbed) conditions from 1952 pre-Whiskeytown Dam air photos (Figure 11), acknowledging that the channel had likely recovered from mining impacts to some degree, but not necessarily completely. These photos indicate that Clear Creek was mostly a single thread channel with occasional braiding (Figure 11), supporting the prediction of Leopold and Wolman (Figure 12). The pre-dam 1.5-year flood (surrogate for bankfull discharge) of 5,700 cfs and channel slope of 0.0035 (local slope through the Floodway Rehabilitation Project reach) also corresponds with this inference. Based on the 1952 aerial photos and the 1936 planform map, pre-Whiskeytown Dam meander wavelengths ranged between approximately 1,200 ft and 2,300 ft, with a best pre-dam prediction of 1,600 ft in the project reach.

Historical air photos and remnant undisturbed reaches suggest that Clear Creek had a moderately defined bankfull channel, with functional floodplains and frequently accessed high flow scour channels on upper bar and floodplain surfaces (Figure 11). Remnant floodplains are still evident along the lower Clear Creek corridor, and contain deep depositional strata of fine sediments. Old cottonwoods and valley oaks on these historical floodplains are now perched above the stream as a result of channel downcutting and reductions in the flow regime. Channel migration during moderate flood events, and channel avulsion during very large floods, formed oxbows and sections of abandoned channel that, in turn, supported large stands of riparian vegetation. An alternate bar morphology was present (Figure 10) and combined with semi-braided form, created an extremely complex channel morphology.

Alteration to the natural channel morphology in alluvial reaches has been extensive. Downstream of Clear Creek Bridge, alluvial bars, floodplains, and terraces were first placer mined, then dredged for gold. Mining destroyed most of the morphological features of the natural channel and floodplains. Flow and sediment regulation followed, beginning in 1903 with construction of Saeltzer Dam, and continued with completion of Whiskeytown Dam in 1963. Regulation caused significant impacts to channel morphology, including:

- loss of alluvial sediment storage (gravel/cobble) in the canyon below Whiskeytown Dam (Coots, 1971);
- riparian encroachment along the low flow channel, and partial or complete fossilization of alluvial deposits downstream of Clear Creek bridge (Pelzman 1973);
- reduced very fine sediment supply and high flows to suspend them, reducing silt deposition on floodplains and reduced natural riparian regeneration, and floodplain formation processes;
- reduced high flow regime that decreased the ability of the Clear Creek channel downstream of Clear Creek Bridge to migrate or avulse, transport bedload, form floodplains, and keep riparian vegetation from maturing along the low flow water edge;
- Channel incision to clay hardpan in many locations, general bed coarsening, and loss of alluvial storage in the reach downstream of Clear Creek Bridge, resulting from riparian confinement, lost coarse sediment supply from the upper watershed, and downstream aggregate mining.

The existing thalweg profile shows a step-pool profile, with clay hardpan horizons forming the steep steps, intermittent with long, relatively flat run/pools. Aggregate extraction followed by large floods caused rapid and extensive local channel down-cutting, which then caused head-cutting that migrated upstream.

2.5.1.4. Floodplain processes

Adjacent to the active channel and frequently covered in thick patches of riparian vegetation, floodplains are often viewed as a morphological feature distinct from the bankfull channel. Floodplains, however, are

FIGURE 11. LOWER CLEAR CREEK
1952 AERIAL PHOTOGRAPH OF REACH 4
SHOWING MEANDERING/SEMI-BRAIDED CHANNEL MORPHOLOGY

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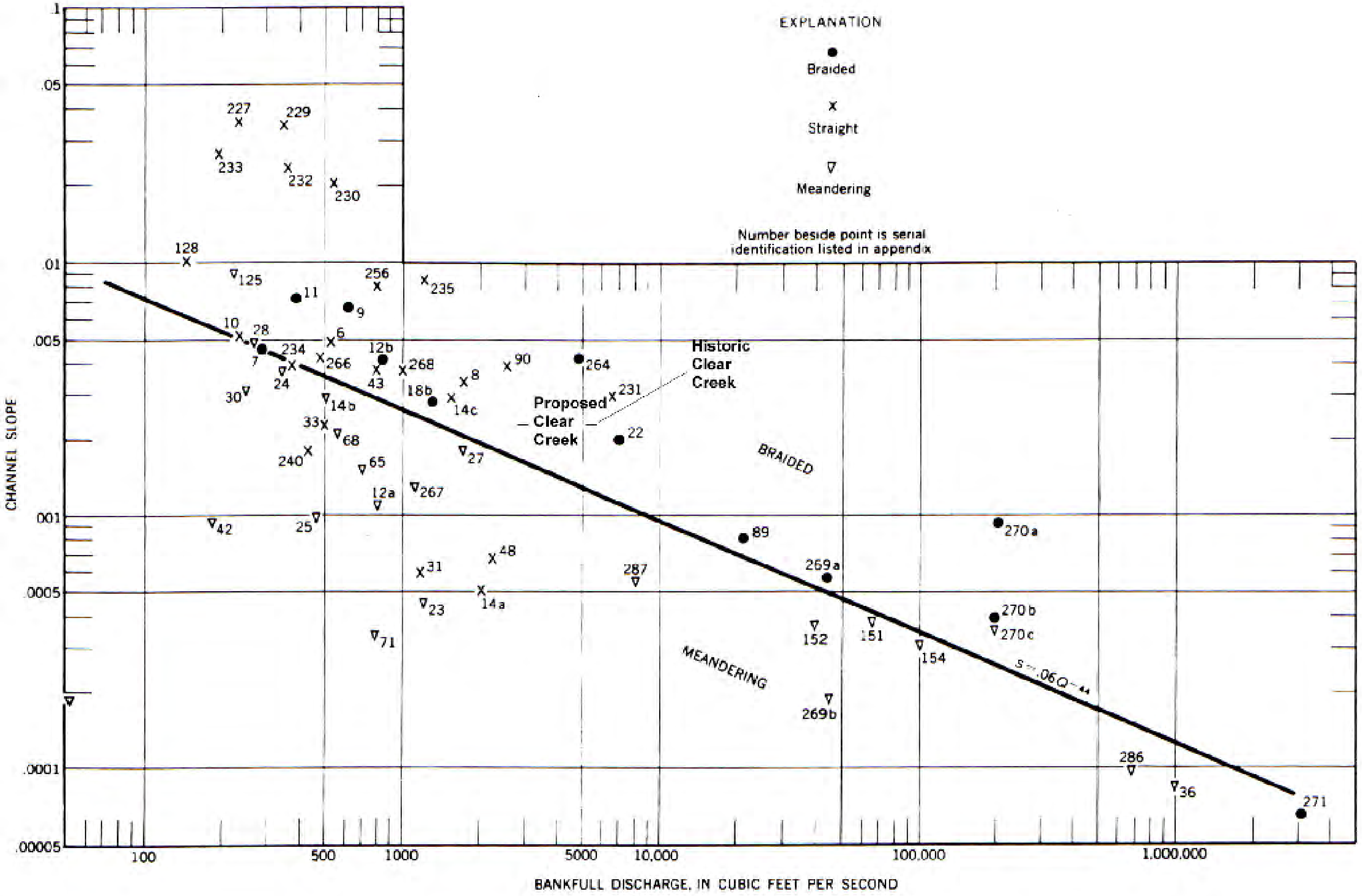

FIGURE 12. RELATIONSHIP BETWEEN BRAIDED AND MEANDERING CHANNEL FORM, PREDICTING CLEAR CREEK REACH 3A AND 4 IN THE TRANSITION BETWEEN MEANDERING AND BRAIDED CHANNEL MORPHOLOGY

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integral parts of a functioning river channel. Not only do fluvial processes form floodplains, but they also influence geomorphic processes in the adjacent river channel. By definition, the floodplain is the flat area adjoining the river channel *constructed by the river* in the present climate and overflowed at times of high discharge (Dunne and Leopold 1978). As mentioned, the floodplain in meandering rivers is deposited gradually as the river channel migrates across the valley floor. At times of high discharge, the floodplain becomes inundated, providing a large storage reservoir for flood waters and dampening the downstream propagation of floodwaters. On the floodplain surface, vegetation slows water velocities, which allows fine sediment (silts and sand) to settle out and deposit. These deposits maintain the floodplain elevation, and contribute to creating rich, fertile soils characteristic of river valley floors. Meandering and semi-braided rivers like Clear Creek had less developed floodplains than lower gradient Central Valley rivers. Floodplains often had variable topography, high flow scour channels, and large woody material.

The change in elevation of a river channel is the net effect of complex processes, but if the river channel incises into the valley floor over time, floodplains become inaccessible to contemporary flood stages and are abandoned. An abandoned floodplain is called a terrace (Dunne and Leopold 1978). In geologic time, an alluvial river often adjusts its channel and floodplain morphology through channel migration and deposition of new floodplains, avulsion and scouring of new channels, erosion into old terrace deposits, and abandonment of old floodplains. These processes create a mosaic of landscape forms in a river valley.

The stored alluvial material composing floodplain and terrace deposits was the material targeted by commercial mining operations. Aggregate mining excavated the entire floodplains, exported the alluvial sediments, and left deep pits in their place. Gold dredging excavated the floodplains (and channelbed) sediments, filtered out the gold, then redeposited the sieved material in cobble rows. The resulting degraded channel (floodway) thus lacked the essential material to rebuild the natural channel and floodplain morphology, and has remained in this degraded condition.

2.5.1.5. Riparian vegetation and fluvial processes

Riparian vegetation is water-dependent. Surface water inundation along flood-prone bottomlands provides the moist seed beds and fine sediments essential to initiate seed germination, and the extent of groundwater influence defines the riparian corridor width and the plant assemblages that grow there. Because of the complexity of interactions between the timing and duration of inundation patterns, the micro-topography of channel, bar, and floodplain features, and the seasonal availability of viable seeds, riparian vegetation typically grows as a mosaic of vegetation patches, or *stands*. In some circumstances these stands form contiguous, dense, lush gallery forests; in others, stands are intermittent among barren, unvegetated areas. A stand is frequently characterized by a particular species composition, which are classified as *plant series* (Sawyer and Keeler-Wolf 1995). Plant series usually contain multiple species, but are classified by one or two dominant species.

Under natural conditions, spring snowmelt floods are relatively long in duration and moderate in magnitude. After the flood peak, river water levels decline gradually through summer months in an extended snowmelt recession hydrograph (Figure 4). Floodplains and alternate bar surfaces, freshly scoured and deposited by snowmelt floods, combine with a slowly receding groundwater table to provide ideal conditions for seedling germination. Many riparian hardwoods disperse their annual seeds during the spring snowmelt, thereby discouraging germination within the bankfull channel. Once germination occurs, however, a host of conflicting forces interact to determine survival or mortality. The magnitude of the spring flood influences the elevation (relative to river stage) at which seedlings germinate; higher elevation means a more rapid rate of groundwater drawdown, and therefore increased probability of mortality by desiccation. But this higher bank position also increases the probability of surviving successive years' flood scour. Falling groundwater tables during summer months creates soil moisture gradients, placing strong selective pressures on established plants. Plants die when their roots cannot keep up with the ground water drawdown. The species' unique physiological adaptations influence their chance of survival. For example, some plant species have evolved rapidly growing roots, which “follow” dwindling sub-surface soil moisture created by flow recession (Segelquist et al. 1993). Others species have evolved different strategies to be more tolerant of desiccation (e.g., seed dispersal in fall and germination in spring).

Seedlings that survive the first growing season generally require successive years of drought to survive the winter flood season and become established. Winter floods during wet water years are capable of mobilizing the entire bar surface. Mortality on active bar surfaces is thus high. Surfaces higher on alternate bars and on floodplains require greater magnitude floods for bed surface mobilization, but are more likely to die from desiccation. In these locations, the balance between mortality from desiccation and flood scour occasionally determines a small percentage of seedlings that can establish and become securely rooted deeper than the surface layer. In general, seedlings on active channel surfaces more frequently survive desiccation, but less frequently survive flood scour; seedlings on floodplain surfaces less frequently survive desiccation, but more frequently survive flood scour. Thus, depending on the succession of water year types (wet, dry, etc.), differential mortality plays a key role in stand distribution, species composition, and age structure.

Riparian recruitment is thus periodic. Different sources of mortality can prevented establishment of a viable cohort for many successive years, causing distinct age classes between successful cohorts. This differential survival tends to be patchy, establishing vegetation stands of varying species composition that are eventually able to modify the hydraulic forces that resist scour and instead promote fine sediment deposition. Once plant stands have beaten the odds of survival through the first few years, they are able to recruit to sexual maturity. Riparian stands that develop on floodplains, the valley floor, or other protected areas may eventually survive for many years and become dense gallery forests composed of a canopy of mature native hardwoods, and an understory of diverse shrubs and annuals. Stands that establish in more exposed, steeper –sloped high energy environments can hope for perhaps several years of seed production before bank erosion topples them, or the large magnitude, infrequent flood (recurrence interval >10-30 years) razes the entire stand. The infrequent, large-scale disturbance from major floods was equally important to riparian stand structure, species composition, and age class diversity.

While land use activities have had little visible impact in the bedrock canyon reaches, perhaps the most visible evidence of environmental degradation is on the floodplain within the alluvial reaches. Beginning at Reading Bar (RM 8.4), much of the historic floodplain has been buried under dredger tailing cobbles. The lack of large floods capable of eroding and reworking the tailings has prevented any significant recovery. In many locations, dredger tailings have prevented flows from accessing floodplains altogether; the infrequent floods and lack of sediment supply have subsequently caused the channel to downcut, further confining the channel within artificially high banks. Contemporary floodplains therefore lack geomorphic connectivity to the channel.

In areas where dredger tailings have remained undisturbed, riparian vegetation has established in the low elevation depressions within dredger piles, where groundwater is accessible. Most dredger piles have remained unvegetated. In other floodplain areas, aggregate mining has essentially removed the entire floodplain surface, leaving shallow depressions that have formed extensive wetland complexes. These off-channel ponds are hydraulically connected to the low-flow channel, and further inhibit natural geomorphic functions (sediment transport, etc.) in these reaches. Off-channel ponds also strand juvenile salmonids.

Riparian vegetation in dependent on properly functioning floodplains. In addition to eliminating habitat historically available to riparian vegetation, the wholesale alteration to floodplain surfaces has interrupted the natural regenerative processes, and regeneration of riparian stands has essentially ceased. Existing stands are now maturing in age, becoming senescent, diseased, and are dying. The lack of regeneration has reduced the stand structure and age-class diversity, further reducing the quality of riparian habitat available to birds and other wildlife.

2.5.2. Clear Creek Bedrock Reaches

If alluvial reaches are generally depositional over geologic timescales, then canyon or bedrock reaches are generally erosional, transporting sediments produced in headwaters to the lower river and valley. Clear Creek is no exception to this general rule. The canyon reach has relatively few depositional features because the steep channel gradient and confinement from bedrock walls produces highly turbulent, scouring flows. Long, deep pools broken by steep bedrock cascades dominate the morphology. The heads of cascades resemble pool-tails but have considerably coarser material than pools shaped in alluvium. Pools are paved with large cobbles and boulders, with some coarse sand and small gravel in the interstices. Channel banks are steep bedrock walls with occasional small patches of gravel deposits sparsely dispersed. Vegetation has very little opportunity or suitable habitat within which to take root and survive. The channel morphology is spatially highly variable because of the external control of geology, but has low temporal variability because only infrequent floods are able to exceed the channel-boundary resistance and move the large boulders in the channel (Wohl, 2000). Channel migration and avulsion typically cannot occur because of the valley wall confinement. Sediment supply from the adjacent valley walls can be substantial for certain geologic terrains. However, the Klamath Mountain terrain of Clear Creek tends to produce relatively low volumes of sediment.

The exception to this description is short reaches where the bedrock walls fall away, allowing lateral space for point bars and narrow floodplains to form. This situation occurs at the Peltier Valley site, the Paige-Boulder Creek site (Reach 1), and the short reach at the Igo gaging station.

Alteration to the coarse sediment supply and sediment transport processes in Clear Creek has resulted from three primary impacts: dredge mining for gold, industrial-scale aggregate extraction, and the construction of Whiskeytown Dam. The dredge mining operation began in the late 1800's during the Gold Rush, and this activity was concentrated in the alluvial reaches downstream of Clear Creek Bridge to the Sacramento River. Aggregate extraction from within the Clear Creek channel and contemporary migratory corridor occurred in a discrete 2-mile reach (RM 2.2 to 4.0) in the lower river, beginning in the 1940's. This practice removed hundreds of thousands of cubic yards of aggregate from the channel during 40 years of mining activity, creating several large, deep pits and shallower pits that adjoin the channel and function as off-channel wetlands.

Perhaps the most significant impact to Clear Creek's coarse sediment supply was the construction of Whiskeytown dam. Since Whiskeytown Dam was completed in 1963, it has blocked all coarse sediments recruited from the upper watershed from reaching the lower river corridor. Because of the steep slope and narrow confinement of the upper canyon reaches, channel degradation has occurred fairly rapidly in these reaches. The channel between Whiskeytown Dam and Paige Boulder Bridge (Reach 1) has become incised and rectangular, confined by riparian berms, and the channelbed substantially coarsened by scour and lack of gravel replenishment. The entire canyon reaches down to Clear Creek Bridge are in substantial sediment deficit as a result of high rates of sediment scour and transport of coarse bed material and lack of sediment supply. With the exception of Paige Boulder Creek and the South Fork of Clear Creek, coarse sediment is recruited from the valley walls and a few local areas of bank erosion. Paige-Boulder Creek contributes large amounts of decomposed granitic sand, and in combination with the reduced flood flow regime and valley widening downstream of the Paige Boulder confluence, a large, aggraded delta has formed in the channel.

The evolution of coarse sediment conditions in Clear Creek is illustrated conceptually in Figure 7, beginning with unimpaired conditions and full sediment routing prior to construction of Whiskeytown

Dam (A), then showing the presently impaired conditions in which coarse sediment supply has been impacted from Whiskeytown and Saeltzer Dams and gravel mining (B). All reaches of Clear Creek have been impacted by streamflow and sediment regulation, and only insignificant sediment supplies from small tributary watersheds are available. Lacking supply, the Clear Creek channel has incised in Reaches 3A and 4, and probably increased particle size through bed armoring. These impacts have cumulatively and rapidly degraded the quality and availability of salmonid habitat.

A survey of salmonid spawning habitat was conducted from Whiskeytown dam to Saeltzer Dam in 1971 by California Department of Fish and Game (Coots 1971). The survey quantified spawning habitat upstream of Saeltzer Dam, and compared results to a 1956 USFWS and CDFG joint survey conducted prior to the construction of Whiskeytown Dam. The 1971 CDFG memorandum concluded that since construction of Whiskeytown Dam, salmon spawning potential of Clear Creek had "deteriorated significantly". The 1956 survey quantified 347,288 ft^2 of spawning habitat, compared to only 29,121 ft^2 of usable habitat in 1971, a 91% reduction in available spawning habitat. The memo reported that:

> *"Most of the former classified spawning habitat now consists of stretches of unproductive coarse sand deposits which is due to the reduction of the sediment carrying capacity of the stream coupled with the accelerated erosion and continued sediment delivery by tributary drainages below Whiskeytown Dam. Logging activities in unstable terrain similar to the nearby Grass Valley Creek drainage basin appear to be the major contributor of [decomposed granitic] sediment in Clear Creek" (Coots 1971).*

The particle size distribution from three sediment samples in the CDFG memo (bulk sampling methods unreported) reported a large proportion of the particles (approximately 30% on average) were finer than 12.8 mm (0.5 inch), indicating the spawning gravels were probably highly embedded with coarse-grained sand and fine gravel. Bjornn and Reiser (1991) report (from Thompson 1972) the size range of suitable spawning gravel for chinook salmon to be approximately 13 to 102 mm (0.5 to 4.0 inches).

Salmon spawning gravels were surveyed again in 1982 as part of the instream flow study (California Department of Water Resources 1986). Examination of the spawning gravels in 1982 found that the percentage of fine sediment (< 1-inch diameter) in spawning gravels had increased substantially, comprising 47 to 68 percent of the spawning beds. None of the spawning gravels sampled in 1982 satisfied CDFG criteria for suitable spawning gravel.

The US Fish and Wildlife Service has implemented a monitoring program to evaluate the quality of spawning gravels in lower Clear Creek. In 1997 and 1998, they collected bulk samples using a 12-inch diameter McNeil sampler. Samples were collected from spawning gravels at nine sites, with 4 to 5 bulk samples per site. Samples were sieved wet and each fraction measured by volumetric analysis. Data from two years (81 bulk samples) revealed that spawning gravels in the lower Clear Creek corridor are highly impacted; on average, approximately 50% and 48% of substrate (for 1997 and 1998 data, respectively) were composed of particles finer than 13mm, well outside the range suitable for spawning.

2.5.3. Biological Links to Fluvial Processes

Alluvial rivers are generally considered hot spots of biodiversity resulting from high rates of energy and nutrient input, storage, and transport (Tietje et al. 1991, Stanford et al. 1996, Williams et al. 1999). Expansive floodplains with nutrient-rich soils and shallow groundwater, and high annual variability in streamflow and temperature regimes, also contribute to high biodiversity. Within alluvial reaches, the river's morphology governs its habitat structure; alternating point bars and associated riffles and pools are the primary geomorphic units of alluvial rivers, and represent a key habitat template for all freshwater life stages of anadromous salmonids, as well as for other river biota. Figure 10 illustrates the diverse habitats found within the alternate bar sequence. The topographic diversity of the channelbed and active bar surfaces provides diverse salmonid habitats, including:

- adult holding in pools;
- spawning substrate in pool tails and riffles with suitable hydraulic conditions (depth and velocity) and substrate size (gravels and small cobbles);
- egg incubation environment with subsurface flow;
- winter and spring rearing in the shallow margins of bars and in backwater zones;
- summer rearing in deeper, thermally stratified pools;
- fry and juvenile refugia on undated floodplain surfaces during winter and spring floods;
- abundant food production areas;
- large organic debris load and nutrient retention zones.

The quality of many of these critical habitat components depends integrally on the supply, storage, and transport of coarse sediments within alluvial reaches. Salmonid spawning habitat, for example, requires a well-sorted distribution of gravel and small cobbles, frequent mobilization from winter floods to flush fine sediments, and a channelbed morphology that creates suitable hydraulic conditions for spawning and egg incubation. The highest quality rearing habitat for salmonid fry is often found along the shallow, slow velocity margins of alternate bars, where coarse sediments provide interstitial hiding places, productive invertebrate (food) habitat, and access to high flow refugia on top of lateral bars. While bedrock reaches tend to be less productive, local reaches where valley width and/or channel gradient allows coarse sediment to deposit are very important biologically (e.g. Peltier and Paige-Boulder sites in Reach 1).

2.5.4. Geomorphic Reach Delineation

The 17-mile long lower Clear Creek corridor exhibits obvious and fundamental differences as the stream transitions from Whiskeytown Dam to the Sacramento River. Four distinct reaches were delineated along lower Clear Creek, based primarily on geomorphic characteristics (e.g., channel slope and confinement, alluvial vs. bedrock channel, extent of floodplains and riparian vegetation, etc.), and secondarily on land-use impacts resulting from dredge mining for gold, aggregate mining, streamflow regulation, and coarse sediment blockage from Whiskeytown and Saeltzer dams. The four reaches are: (1) The upstream, confined, alluvial reach directly below Whiskeytown Dam, (2) the canyon reach from Paige-Bar to Clear Creek Bridge, (3) the alluvial reach upstream of the Saeltzer Dam site, and (4) the alluvial reach downstream of the Saeltzer Dam site. This reach delineation is useful to describe the specific geomorphic conditions of each reach, and to provide a context for identifying specific ecological stressors (CALFED 1999), different anadromous salmonid issues, and developing restoration actions and strategies that target specific features of the different reaches. An obvious example of the differences between reaches is the upper bedrock gorge and the lower alluvial reach, each with fundamental geomorphic and land use differences, and each requiring different restoration treatments/approaches. The following is a brief description of each of the four geomorphic reaches (shown in Figure 2).

<u>Reach 1: Whiskeytown Dam to Paige Bar Bridge (RM 17.5 to 15.4)</u>. This 2.1 mile long *Upstream Alluvial Reach* below Whiskeytown dam is characterized by a narrow, confined gorge with extensive exposed bedrock and deep pools, moderate gradient (1934 water surface slope = 0.0060), and a coarse alluvial bed (primarily cobbles and boulders, with intermittent sand deposits) (Figure 13). Located within the Klamath Mountain province, the channel has relatively little floodplain area, and moderate alluvial storage. The dominant vegetation is alder and willow, and riparian vegetation is generally confined to a narrow strip along the channel (Figure 13). The narrow canyon widens in two short portions of this reach, at the Peltier Bridge where a sharp 180° bend allows a large alluvial bar, and at Paige-Bar, where the wider channel combined with the large contribution of fine sediment from Paige-Boulder Creek (primarily decomposed granite as coarse sand) has formed alluvial bars and a meandering channel. Prior to completion of Whiskeytown and Saeltzer Dams, the upper half of this reach likely provided high

FIGURE 13. LOWER CLEAR CREEK CHANNEL AT THE TRANSITION BETWEEN REACH 1 & REACH 2

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quality over-summer holding habitat for spring-run chinook salmon and steelhead, before they migrated further upstream in the fall to spawn. There is potential to restore this summer holding habitat for these species due to the removal of Saeltzer Dam. The Peltier Bridge site is slightly more alluvial and could provide a substantial amount of spawning habitat with additional gravel introduction efforts.

<u>Reach 2: Paige Bar Bridge to Clear Creek Bridge (RM 15.4 to 8.4)</u>. Below Paige Bar Bridge, Clear Creek enters a 7 mile long *Canyon Reach* in which the river is narrowly confined between steep, confining bedrock bluffs (Figure 14). This reach is also located within the Klamath Mountains province. The average slope from 1934 water surface profiles is approximately 0.0079, but is typified by long, deep bedrock pools interrupted by short, steep cascades. Pool depths reach 10 to 15 ft in many portions of the reach. The channel bed is composed of bedrock and boulder, with a limited supply of grave and sand along banks and in lee deposits behind large bedrock features. Floodplains do not exist, and riparian vegetation is confined to a narrow band along channel margins. Sediment routing through this reach would be expected to be very rapid. Similar to Reach 1, this reach had relatively low impacts directly from land use, primarily because these types of high energy reaches are less sensitive than alluvial reaches. Some riparian encroachment has occurred due to Whiskeytown Dam. Over-summer holding habitat for chinook salmon and steelhead is extensive in this reach, especially due to the cold water temperatures from hypolymnial releases from Whiskeytown Reservoir, and the lack of sun exposure. The USGS gaging station 'Clear Creek nr Igo' is located in the lower portion of this reach, where the channel briefly widens.

<u>Reach 3A: Clear Creek Bridge to Saeltzer Dam gorge (RM 8.4 to 6.8)</u>. Downstream of Clear Creek Bridge on Clear Creek Road, the *Saeltzer Dam Reach* begins the transition from the Klamath Mountains province to the Great Valley province; the river corridor widens and valley walls become more distant (Figure 15). While still shallowly underlain by Klamath bedrock formations, the channel in Reach 3A becomes distinctly alluvial for the 1.6 miles down to Saeltzer Dam. Bed substrates become increasingly finer as the channel gradient from 1934 water surface profiles decreases to approximately 0.0036. The widened floodway allows deposition of alluvial bar features and a slightly meandering channel. Some aggradation has resulted from the backwater effect from Saeltzer Dam (RM 6.8). This reach includes Reading Bar, the site of extensive historical gold and dredger mining activity that degraded much of the floodplain and channel. This alluvial reach also likely provided abundant, high quality salmonid spawning and rearing habitats, and wide stands of mixed riparian vegetation dominated by cottonwood and oak woodland forests, and willow/alder vegetation close to channel margins. Removal of Saeltzer Dam may result in some channel downcutting into the alluvium, and require considerable time for recovery of a natural channel morphology.

<u>Reach 3B: Saeltzer Dam gorge (RM 6.5 to 6.8)</u>. This lower portion of the *Saeltzer Dam Reach* is essentially a short (1,500 ft), steeply sloped gorge (1934 slope = 0.036) below the Saeltzer Dam site, in which Klamath Mountain bedrock formations are last exposed at the surface of the channel (Figure 16). Below this gorge, the transition to an alluvial channel (Great Valley province) is complete. There are several bedrock cascades of five or more foot elevation drop that may pose fish passage problems at low flows. Historically, however, fish commonly accessed reaches upstream of this gorge. Very little riparian vegetation grows within the confines of the gorge.

<u>Reach 4: Saeltzer Dam gorge to Sacramento River (RM 6.5 to 0.0)</u>. The *Unconfined Alluvial Reach* extends 6.5 miles from the Saeltzer Dam gorge to the Sacramento River confluence, and is characteristic of the Great Valley province. The wide floodway (greater than 500 ft) and lower slope (0.0023) combine to form a low gradient, meandering channel with extensive sediment deposition and storage. Floodplains are wide, and support large stands of diverse riparian vegetation, dominated by willow and cottonwood hardwood forests. Gold mining and aggregate mining severely damaged this reach (Figure 17).

FIGURE 14. LOWER CLEAR CREEK CANYON IN REACH 2

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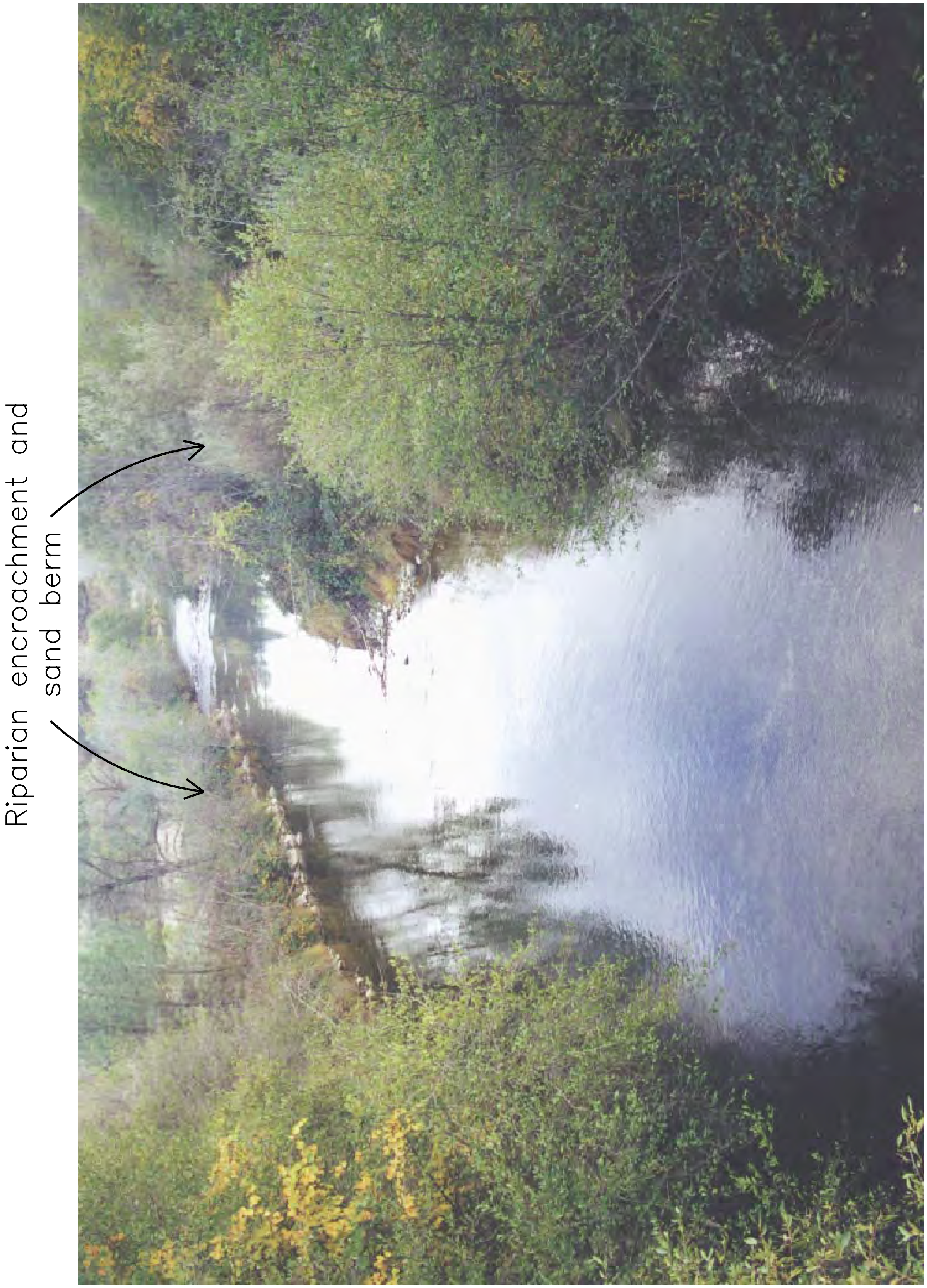

FIGURE 15. LOWER CLEAR CREEK
CLEAR CREEK ROAD BRIDGE LOOKING DOWNSTREAM INTO REACH 3A

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FIGURE 16. LOWER CLEAR CREEK CHANNEL IN REACH 3B AT THE FORMER SAELTZER DAM SITE GORGE

12/6/01

FIGURE 17. LOWER CLEAR CREEK IN REACH 4
AT THE FLOODWAY REHABILITATION PROJECT SITE (1997),
SHOWING LOW GRADIENT CHANNEL AND IMPACTS OF INSTREAM AGGREGATE MINING

12/6/01

Gravel mining removed thousands of tons of aggregate, and left large pits in former floodplains that function as shallow wetlands. Despite the extensive degradation in the “Gravel Mining Reach”, this reach still provides the best quality salmonid habitat available in lower Clear Creek and supports the remaining population of fall-run chinook salmon. This portion of Reach 4 is undergoing extensive reconstruction to restore the alluvial channel morphology and salmonid spawning and rearing habitats, and to reduce stranding mortality caused by off-channel gravel pits.

2.6. Attributes of a healthy river ecosystem

The foundation of a river ecosystem is the dynamic interaction of flowing water, sediment, and riparian vegetation. We define an alluvial river as one that is able to form its bed and banks with alluvium under the current flow and sediment regime. Regulation of flow and sediment on many historically alluvial rivers has been so severe, that they no longer are able to form their own bed and banks (thus, we consider them no longer alluvial rivers). The channel bed and banks of steep mountain rivers are typically bedrock, and thus are usually considered non-alluvial (with the exception of local valley width expansions that allow local alluvial features to form).

River ecosystems are extremely complex, and adding flow and sediment regulation only adds to this complexity when faced with developing rehabilitation measures. Simplifying river biological functions into a set of principles that address a broad range of rivers is difficult at best, and attempting to predict biological cause-and-effect relationships often carries with it a high degree of uncertainty. However, some simplification can occur if we acknowledge that fluvial geomorphic processes sustain a river ecosystem’s structure and function. Therefore, managing regulated rivers by restoring natural geomorphic processes, within contemporary sediment supply and flow constraints to the greatest extent possible, is a realistic startup strategy for restoring and managing river ecosystems. We first present a set of ten **alluvial** river attributes that can be used as guidelines (hypotheses or targets) for recovering and/or preserving critical geomorphic and hydrologic processes that sustain an alluvial river ecosystem. We then present a set of **bedrock river** attributes that can be used to describe the structure and function of the Clear Creek canyon reaches upstream of the Clear Creek Bridge.

2.6.1. Alluvial River Attributes

The following alluvial river attributes are appropriate for Reach 3A and 4 on lower Clear Creek, as these reaches were historically wider, lower gradient, and alluvial.

Alluvial Attribute No. 1. *The primary geomorphic and ecological unit of an alluvial river is the alternate bar sequence. Dynamic alternating bar sequences are the basic structural underpinnings for aquatic and riparian communities in healthy alluvial river ecosystems.*

The fundamental building block of an alluvial river is the alternate bar unit, composed of an aggradational lobe or point bar, and a scour hole or pool (Figure 10). A submerged transverse bar, commonly called a riffle, connects alternating point bars. An alternate bar sequence, comprised of two alternate bar units, is a meander wavelength; each wavelength is between 9 to 11 bankfull widths (Leopold 1964). The idealized alternate bar sequence is rarely found in nature, because natural geomorphic variability (e.g., valley width contractions, bedrock exposures, etc.) perturbs the idealized channel form shown in Figure 10. Floods flowing through alternating bar sequences frequently re-arrange the bar topography, producing diverse, high quality aquatic and terrestrial habitat.

Alluvial Attribute No. 2. *Each annual hydrograph component accomplishes specific geomorphic and ecological functions. Annual hydrograph components (including winter storm events, baseflows, snowmelt peaks, and snowmelt recession limbs) collectively provide the impetus for processes that shape* *and sustain alluvial river ecosystems. These components are uniquely characterized by year-to-year variation in flow magnitude, duration, frequency, and timing.*

Hydrograph components are seasonal patterns of daily average flow that recur from year-to-year. For many rivers in the western U.S., these include summer baseflows, rainfall and rain-on-snow generated floods, winter baseflows, snowmelt peak runoff, and snowmelt recession (Figure 4). Each annual hydrograph component can be characterized by its inter-annual variability in flow magnitude, duration, frequency, and timing. A subset of all processes needed to create and sustain alluvial river ecosystems is provided by each hydrograph component. Eliminate or alter the inter-annual variability of the hydrograph components, and the ecosystem is invariably altered.

Alluvial Attribute No. 3. *The channelbed surface is frequently mobilized. Coarse alluvial channelbed surfaces are significantly mobilized by bankfull or greater floods that generally occur every one to two years.*

As streamflow rises throughout a winter storm and during peak snowmelt, a geomorphic threshold for mobilizing the channelbed surface is eventually exceeded. This flow threshold typically occurs over a narrow range of streamflow and varies spatially, depending on the morphology, grain size, and location of sediment deposits (Figure 18). In general, grains on the channelbed surface are mobilized many times a year, but sometimes not at all in other years, such that, over the long-term, the streambed is mobilized on the order of once a year. The duration of channelbed mobilization is a function of the duration of the high flow, which is typically on the order of days.

Alluvial Attribute No. 4. *Alternate bars must be periodically scoured deeper than their coarse surface layers. Floods that exceed the threshold for scouring bed material are needed to mobilize and rejuvenate alternate bars. Alternate bars are periodically scoured deeper than their coarse surface layer, typically by floods exceeding 5-yr to 10-yr annual maximum flood recurrences. Scour is generally followed by re-deposition, often with minimal net change in the alternating bar topography.*

Complex alternating bar sequences are partly created and maintained by providing the natural frequency and intensity of bed scour dependent on discharges that vary in magnitude and duration. During the rising limb of a hydrograph, after the bed surface begins to move, the rate of gravel transport rapidly increases and the bed surface begins to scour. The degree of scour can be significant, up to several feet deep. Infrequent, wet years typically generate storms with a high magnitude and long duration; scour depth will be substantial. On the receding limb of a flood hydrograph, gravel and cobbles re-deposit, often resulting in no net change in channelbed elevation following the flood.

Alluvial Attribute No. 5. *Fine and coarse sediment budgets are balanced. River reaches export fine and coarse sediment at rates approximately equal to sediment input rates.*

Although the amount and mode of sediment stored may fluctuate within a given river reach, channel-wide morphology is sustained in dynamic quasi-equilibrium when averaged over many years. The magnitude and duration of high flows surpassing a flow threshold for channelbed mobility are critical for balancing the sediment budget. Chronic channelbed aggradation and/or degradation are indicators of sediment budget imbalances. A balanced coarse sediment budget implies bedload continuity; that is, the coarser particle sizes comprising the channel bed must be transported through alternate bar sequences.

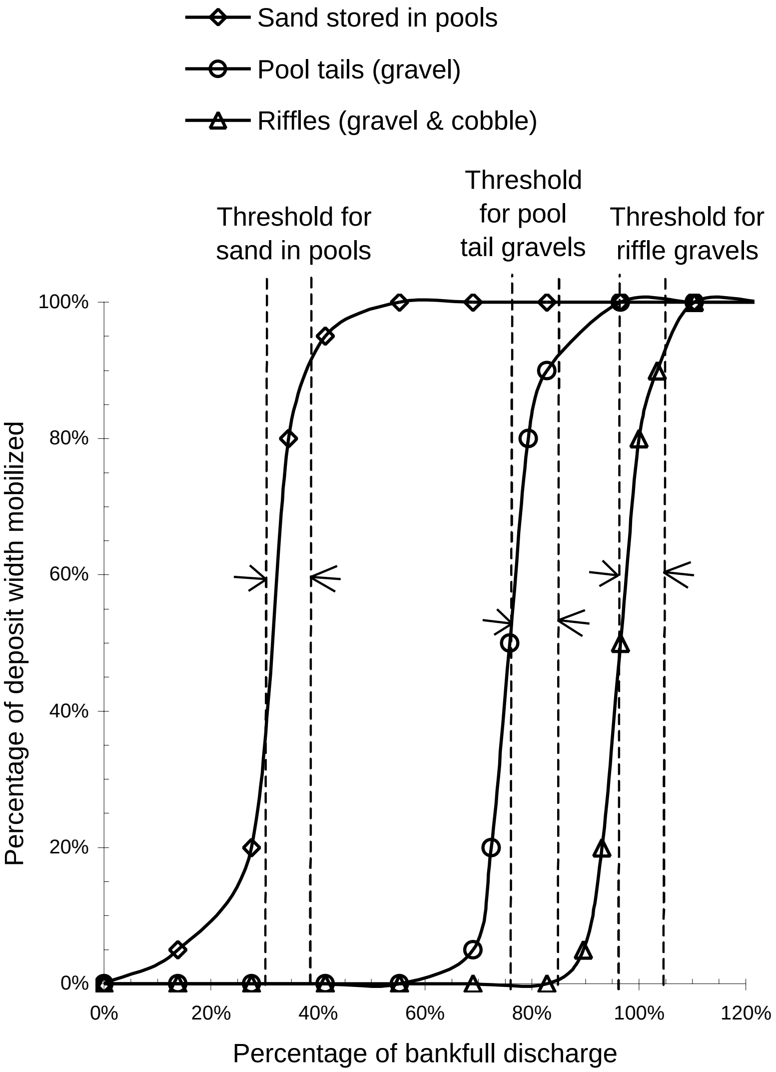


Figure 18. Conceptual bed mobilization patterns for diverse substrate patches in alluvial channels.

Alluvial Attribute No. 6. *Alluvial channels are free to migrate. During lateral migration, the channel erodes older flood plain and terrace deposits on the outside bend while depositing sediment on the bar and flood plain of the inside bend. Though outer and inner bend processes may be caused by different hydrograph components, the long-term result is maintenance of channel width.*

Channel migration is one of the most important processes creating diverse aquatic and terrestrial habitats: sediment and woody debris are delivered into the river and flood plains are rebuilt on the inside of the meander. That the stream has occupied numerous locations in its valley is evidenced by direct observations of its movement over time, and by indirect evidence obtained if one digs deeply enough into the flood plain. Gravel and cobbles laid down by the river many years before will be found. The channel does not typically migrate during periods of low flow, but migrates during flows approaching and exceeding bankfull discharge. Shear stress on the outside of bends exceeds that necessary to erode the materials on the outside of the bank. In lower gradient reaches of alluvial rivers, migration tends to be more gradual.

Alluvial Attribute No. 7. *Flood plains are frequently inundated. Flood plain inundation typically occurs every one to two years. Flood plain inundation attenuates flood peaks, moderates alternate bar scour and promotes nutrient cycling.*

As flows increase beyond that which can be contained by the bankfull channel, water spreads across the flatter flood plain surface. The threshold for this process is the bankfull discharge. This first threshold allows flow to simply spill out of the bankfull channel and wet the flood plain surface; a slightly larger discharge is required to transport and deposit the fine sediments that are in suspension. Flood plain inundation also moderates alternate bar scour in the mainstem channel by limiting flow depth increases within the bankfull channel during floods. As water covers the flood plain, flow velocity decreases. Sediment begins to settle, causing fresh deposits of fine sands and silts on the flood plain. This deposition promotes riparian vegetation regeneration and growth.

Alluvial Attribute No. 8. *Large floods create and sustain a complex mainstem and flood plain morphology. Large floods--those exceeding 10-yr to 20-yr recurrence events--reshape and/or redirect entire meander sequences, avulse mainstem channels, rejuvenate mature riparian stands to early-successional stages, form and maintain side channels, scour flood plains, and perpetuate off-channel wetlands including oxbows.*

A still larger flow threshold than floodplain inundation is one that scours the flood plain. The streamflow necessary to surpass this threshold is typically many times the bankfull flow because shear stress on the vegetated flood plain surface must be high enough to cause scour. Infrequent large floods are critical for sustaining channel complexity because they change river location and morphology on a large scale, and prevent riparian vegetation from dominating the river corridor.

Alluvial Attribute No. 9. *Diverse riparian plant communities are sustained by the natural occurrence of annual hydrograph components. Natural, inter-annual variability of hydrograph components is necessary for woody riparian plant life history strategies to perpetuate early- and late-successional stand structures.*

Native riparian plant communities characteristic of alluvial river ecosystems are adapted to, and thus sustained by, a constantly changing fluvial environment. The magnitude and duration of annual hydrograph components needed for alternate bar scour, channel migration, floodplain inundation and scour, and channel avulsion provide necessary substrate conditions for successful seedling establishment and stand development. The timing and frequency of annual hydrograph components must coincide with seasonally-dependent life history requirements, such as the short window of time when riparian plants are dispersing seeds. A sustainable supply of large woody debris (LWD) from the riparian zone ultimately depends on variable age classes of woody riparian vegetation and a migrating channel.

Alluvial Attribute No. 10. *Groundwater in the valley bottomlands is hydraulically connected to the mainstem channel. When flood plains are inundated, a portion of surface runoff from the watershed is retained as groundwater recharge in the valley bottomlands.*

The river corridor is hydraulically interconnected. Groundwater in the floodplain is closely connected to mainstem flows, and can be periodically recharged by mainstem flooding. Avulsed meander bends often create oxbow wetlands, which retain direct hydraulic connectivity to mainstem surface flows.

2.6.2. Bedrock River Attributes

The following bedrock river attributes are appropriate for Reach 1, 2, and 3B on lower Clear Creek, as these reaches were historically confined, steeper gradient, and bedrock controlled.

Bedrock Attribute No. 1. *Bedrock/boulder channels are predominately erosional environments, but do have alluvial deposits. Alluvial deposits are sporadic, and smaller size deposits are usually nested within larger deposits. These nested deposits are the structural underpinning of bedrock/boulder dominated channel morphology. These deposits occur at a different spatial and temporal scale than for alluvial channels*.

Generally there appears to be three levels of depositional nesting: (1) the largest scale is often a function of local geomorphology, where the canyon walls constrict flood flows, creating huge backwater environments for many channel widths upstream, (2) the depositional of boulder sets from the largest hydraulic control creates a nested depositional feature, where small boulders are deposited upstream, and (3) gravel and cobble deposition occurs where very local hydraulic controls create eddy deposits (actually several kinds of depositional features within the active channel). Each hydraulic control requires different hydrograph components identified in Bedrock Attribute No. 2.

Bedrock Attribute No. 2. *Inter-annually variable hydrograph components create/sustain this natural sequence of nested hydraulic controls and provide the necessary physical template for ecological diversity and integrity*.

This simply states the importance and relationship of annual hydrograph variation to mobility thresholds of different depositional features, as was the case for the Alluvial River Attributes.

Bedrock Attribute No. 3. *Finer-grained depositional features (gravels and cobbles) are shaped and maintained by common floods in the 1.5 to 5 year recurrence interval. Transport distances and turnover rates for these deposits are large.*

These features are particularly prevalent along the channel margins and in the lee of boulders within the channel. These in-channel deposits often constitute a majority of salmonid spawning gravel deposits and finer grained deposits for riparian establishment.

Bedrock Attribute No. 4. *Coarse-grained depositional features (small-medium boulder bars) are shaped and maintained by flood hydrographs with minimal annual recurrence intervals of 5 to 10 years.*

Large hydraulic controls, such as valley wall constriction and/or large boulder, cause boulder bars to form on the upstream side of the control. These deposits are periodically mobilized, as evidenced by their rounded edges and impact marks from downstream transport, but are only mobilized by larger floods in the 5 to 10 year recurrence interval range. Transport distances and turnover rates for these deposits are small.

Bedrock Attribute No. 5**.** *Large hydraulic control features (extremely large individual boulders in the channel) are shaped and maintained by flood hydrographs with minimal annual recurrence intervals of over 25 years.*

Large boulders that cause significant hydraulic control during moderate to high flows are delivered to the stream from the adjacent hillslope, and are infrequently recruited and mobilized by high flows greater than 25 year recurrence. These larger boulders are typically very angular, with rounding caused by bedload and suspended load abrading it rather than from abrasion from the boulder being transported downstream. Transport distances and turnover rates for these deposits are extremely small, often with particle travel distances less than 50 ft.

Bedrock Attribute No. 6. *Coarse sediment transport rates are influenced greatly by sediment supply in addition to hydraulic conditions.*

Because of the smaller amount of alluvial storage in bedrock streams, coarse sediment transport is increasingly driven by local supply from the watershed rather than by hydraulic transport capacity. As drainage area decreases, the reliance on sediment supply from the watershed becomes more dominant than hydraulic conditions during high flows.

Bedrock Attribute No. 7. *Coarse sediment storage volume is a function of "storage reservoirs" in the channel rather than sediment supply.*

There are inflections in the amount of coarse sediment storage capable in a bedrock channel that is a function of roughness elements that cause depositional features (boulder lee, channel margin, bedrock extrusion). Exceeding this storage volume limitation requires an extremely large coarse sediment supply to exceed the large transport capacity of these channels. Nearly all sorted patches of gravels and cobbles are associated with these roughness elements (shear stress shelters), and their turnover rates can be similar to those of alluvial channels.

Bedrock Attribute No.8. *Periodic cleansing of accumulated cobbles and gravels in pools is necessary to maintain pool morphology*.

Reduction in the magnitude and frequency of floods may allow local hillslope-derived boulders and cobbles to accumulate in pools. Pool morphology is maintained by larger floods causing a hydraulic jump at the downstream end of a cascade and in the pool. As large boulders enter from the valley walls, there must be some mechanism preventing their build-up at the bottom of deep pools.

Bedrock Attribute No. 9. *Ecological hotspots occur at valley width expansion zones, where atypical short channel segments exhibit alluvial characteristics that provide more extensive and higher quality aquatic and terrestrial habitats.*

Bedrock rivers often have a small number of atypical valley width expansions that reduce hydraulic forces during high flows, and allow larger scale alluvial features to form and persist. These small alluvial sub-units within the high energy bedrock channel morphology provides important habitat to many species (riparian forest, spawning gravels), and may provide hydraulic refugia during high flow events.

Bedrock Attribute No. 10. *The variable hydrograph of bedrock rivers sustain the hyphoreic zone, and is hydraulically connected throughout the river corridor floor.*

Bedrock dominated channels have lateral standing water and wetland habitats that are sustained by instream flows. These areas provide significant reptile and amphibian habitat.

3. STUDY OBJECTIVES

The overarching goal for management and restoration in lower Clear Creek is to re-establish critical ecological functions, processes, and characteristics, within contemporary regulated flow and sediment conditions, that best promotes recovery and maintenance of resilient, naturally reproducing salmonid populations and the river's natural animal and plant communities. This goal is supported by the lower Clear Creek Coordinated Resource Management Program (CRMP), the US Bureau of Reclamation, the CALFED Bay-Delta Ecosystem Restoration Program, Central Valley Project Improvement Act (CVPIA), and the Anadromous Fish Restoration Program (AFRP). The Attributes of Alluvial and Bedrock River Integrity listed above provide initial hypotheses of how these types of streams function in a proper manner, thus can be used to develop restoration or rehabilitation objectives. The goal of the *Geomorphic Investigation* is to begin quantifying important geomorphic thresholds and rates for different reaches of lower Clear Creek. Specific objectives are to begin:

1. Quantifying the streamflow threshold for mobilizing coarse sediment deposits (Attribute 3)
2. Quantifying relationships between streamflow and bed scour of coarse sediment deposits (Attribute 4).
3. Quantifying or estimating coarse sediment transport rates in different reaches of the stream to assist evaluating the coarse sediment budget (Attribute 5).

Providing this important geomorphic information will assist management agencies develop future channel restoration designs, implement coarse sediment management, and identify channel maintenance flow needs.

4. STUDY SITES

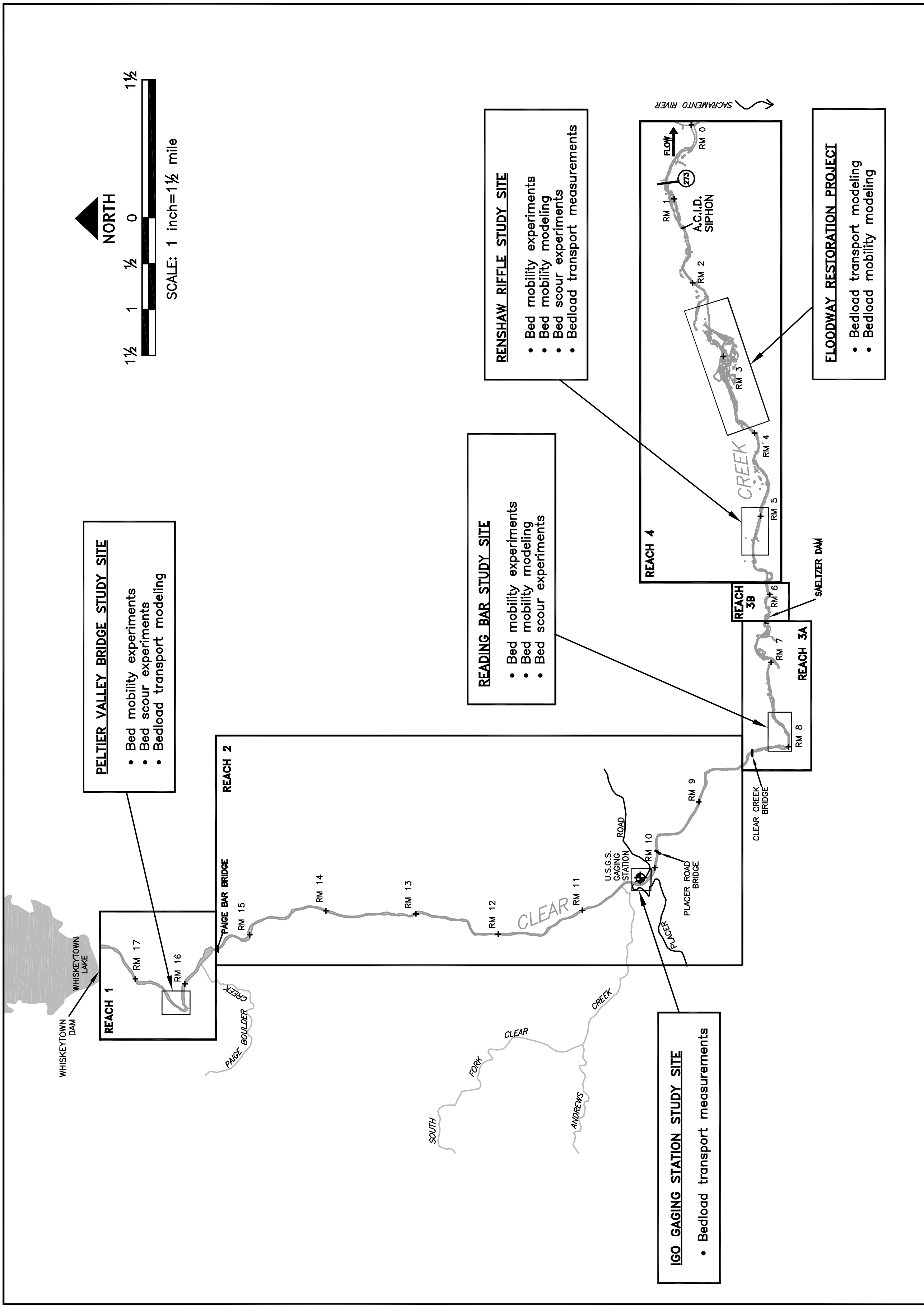
To satisfy the objectives listed above, we had to identify and select study sites that adequately represented geomorphic diversity within the Clear Creek corridor downstream of Whiskeytown Dam. Geomorphic thresholds and processes can be quite different between the four reaches identified in Figure 2, thus we attempted to establish at least one study site within each reach. Within the 16-mile lower Clear Creek corridor, alteration to the natural channel and floodplain form by gravel mining and the effects of Whiskeytown Dam has been so extensive that locating study sites appropriate to evaluate study objectives was quite challenging. With the exception of one alternate bar sequence at the Reading Bar site (RM 7.7), most other meander sequences are relics of the pre-Whiskeytown Dam channel morphology fossilized by riparian berms. Regardless, we established the following study sites (Figure 19):

SITE	PURPOSE
Peltier Valley Bridge study site:	Bed mobility and scour experiments, bedload transport modeling
Igo Gaging Station study site:	Bedload transport measurements
Reading Bar Study Site:	Bed mobility and scour experiments
Renshaw Riffle Study Site:	Bed mobility and scour experiments, bedload transport measurements, bed mobility modeling
Floodway Rehabilitation Project:	Bedload transport modeling

The Peltier Bridge site was chosen because a forced meander bend downstream of the bridge that had a variety of active alluvial features (point bar, pool-tail spawning deposits, lee deposits), and a long straight reach upstream of the bridge suitable for bedload transport modeling. The Igo Gaging Station site was chosen because it reasonably represented gravel supply entering the alluvial reach, had a long hydrologic record at the site, and was in a location favorable to sampling at moderate high flows (up to 5,000 cfs or so). The Reading Bar site was chosen because it was the first alluvial reach out of the canyon, and had one of the few active alternate bar sequences in the alluvial reach. The Renshaw Riffle site is long and straight (suitable for bedload measurements and modeling), contains large areas of suitable spawning habitat used extensively by salmonids, and subtle alternate bars at the upstream end suitable for bed mobility and scour experiments. The Floodway Rehabilitation Project was not necessarily a field-based study site, but the restoration design was used to model bedload transport once restoration was completed. All sites will be useful as long-term monitoring sites if the Clear Creek Restoration Team chooses to use them as such.

4.1. Peltier Valley Bridge Study Site

The Peltier Valley Bridge site, located in Reach 1 from RM 16.2 to 16.5, is approximately one mile downstream of Whiskeytown Dam (Figure 19), is a short semi-alluvial reach within the upper bedrock canyon morphology. This reach is particularly important for newly restored spring-run chinook salmon and winter-=run steelhead access (with removal of Saeltzer Dam) because it is locally lower gradient, can store more spawning gravels due to lower gradient, and is potentially where spring-run chinook salmon and winter-run steelhead would concentrate because Whiskeytown Dam blocks upstream access. The site contains a broad left bank point bar relic of pre-dam morphology. The reach has been placer mined for gold, and the low water edge is now encroached with riparian vegetation, forming a riparian berm over much of the reach. The right bank is steep, oak woodland hillslope. The site contains an active forced alternate bar sequence at the downstream end of the point bar (Figure 20A), with a deep corner pool and pool tail, a medial bar deposit and second pool tail (in sequence moving downstream) (Figure 21).



PELTIER VALLEY BRIDGE STUDY SITE

- Bed mobility experiments
- Bed scour experiments
- Bedload transport modeling

IGO GAGING STATION STUDY SITE

- Bedload transport measurements

READING BAR STUDY SITE

- Bed mobility experiments
- Bed mobility modeling
- Bed scour experiments

RENSHAW RIFFLE STUDY SITE

- Bed mobility experiments
- Bed mobility modeling
- Bed scour experiments
- Bedload transport measurements

FLOODWAY RESTORATION PROJECT

- Bedload transport modeling
- Bedload mobility modeling

FIGURE 19. LOWER CLEAR CREEK GEOMORPHIC EVALUATION
STUDY SITES DOWNSTREAM OF WHISKEYTOWN DAM

12/6/01

A) At Peltier Valley Bridge study site, looking upstream at bedload modeling study site

B) At Peltier Valley Bridge study site, looking downstream at geomorphic study site on left bank point bar

FIGURE 20. LOWER CLEAR CREEK PELTIER VALLEY BRIDGE STUDY SITES

12/6/01

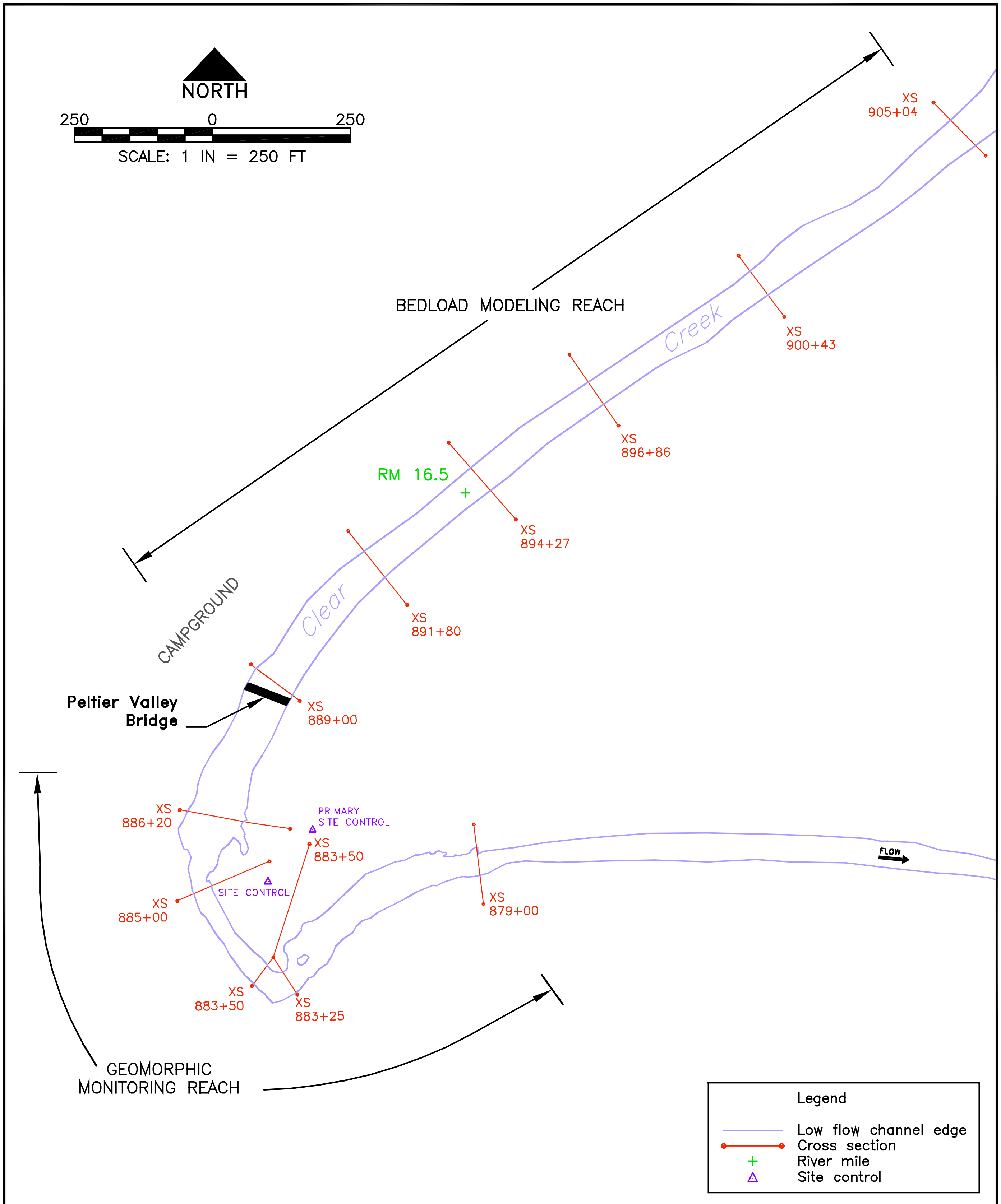


FIGURE 21. LOWER CLEAR CREEK
PELTIER VALLEY BRIDGE GEOMORPHIC & BEDLOAD TRANSPORT MODELING STUDY SITES

12/6/01

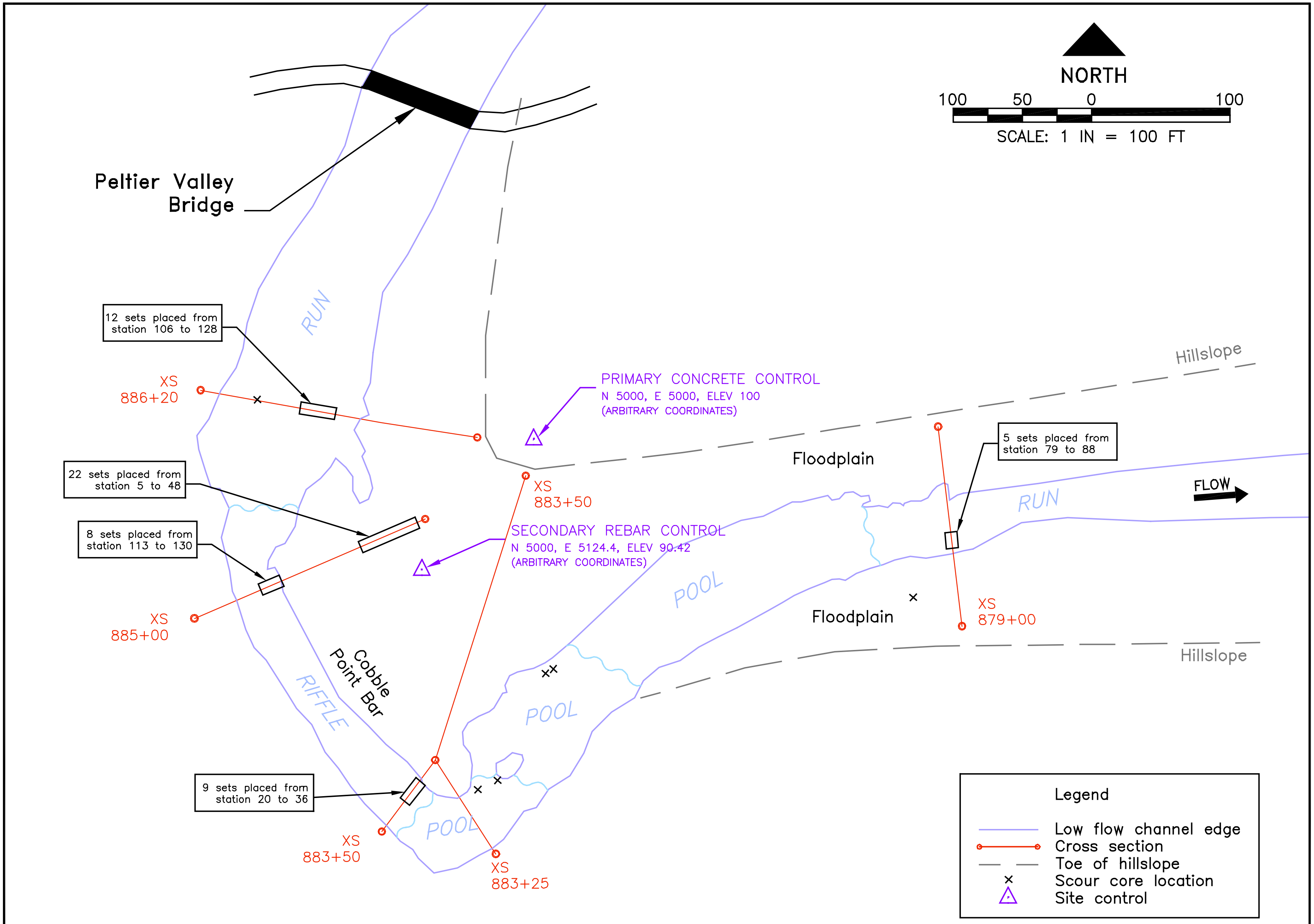
Both pool tails contain coarse gravel deposits suitable for salmonid spawning. The site was chosen because it has rare, active alluvial features that periodically mobilize and scour under the existing flow regime. Additionally, because the Peltier Valley Bridge site is located immediately downstream of Whiskeytown Dam, the flow and sediment regimes at the site are solely a function of Whiskeytown Dam, without any flow or sediment input from unregulated tributaries. Thirteen cross sections were installed (Figure 22), monumented with left and right bank rebar pins, and surveyed to a concrete benchmark with arbitrary northing, easting, and elevation of 5000 ft, 5000 ft, 100.00 ft, respectively. An arbitrary azimuth benchmark was placed 124.4 ft towards the stream, with northing, easting, and elevation coordinates of 5000 ft, 5124.40 ft, 90.42 ft, respectively. Cross sections pins for the bed mobility experiments were surveyed with a total station w/respect to this coordinate system; cross sections upstream of the Peltier Valley Bridge used for the bedload transport modeling were level surveyed w/respect to the arbitrary benchmark datum, but their locations were estimated from longitudinal tape measurements rather than a total station survey. Two scour cores were placed in mobile pool tail deposits, one scour core was placed in a lee deposit behind a boulder, and two sets of tracer rocks were placed on cross sections (Figure 23). Bulk samples from scour cores were sieved for particle size distribution.

4.2. Igo Gaging Station Study Site

The Igo Gaging Station Study Site is located at the UGSG gaging station cableway, approximately 1.8 miles upstream of the mouth of the canyon and a few hundred yards downstream of the mouth of South Fork Clear Creek (RM 10.1) (Figure 19). The site consists of a cross section at the cableway, and two cross sections downstream of the cableway. Bedload samples were collected at the cableway and at the bridge immediately downstream of the cableway (Figure 24). Water surface slopes were surveyed for flows up to 15,800 cfs, and a pebble count was collected to estimate local particle size distribution at the cross section. The local USGS benchmark (H27, elevation=705 ft) on the old Placer Road Bridge railing was used for vertical control at the site, but no horizontal control was used.

4.3. Reading Bar Study Site

The Reading Bar site is located just downstream of where the stream exits the bedrock dominated canyon and enters the low gradient alluvial reach (RM 7.6 to 8.0) (Figure 19). This site was selected to monitor alluvial features associated with the forced meander bar at RM 8.0 and the alternate bar sequence at RM 7.6. The site is also being used to obtain borrow material for the downstream Floodway Rehabilitation Project, where dredger tailings that presently confine the channel will be removed and functional floodplains created. Removal of dredger tailings reversed decades of channel confinement, and future monitoring can observe the evolution of channel morphology resulting from these restoration efforts. The site is located downstream of several tributaries, including Paige-Boulder Creek and South Fork Clear Creek, thus has a larger sediment supply than the Peltier Valley Bridge site, and is much lower gradient than the canyon reaches. Monitoring at this site included bed mobility and scour experiments, sediment composition, and channel geometry (Figure 25). Eleven cross sections were surveyed with engineers levels, and monumented with left and right bank rebar pins. Astro Surveying provided local horizontal and vertical control in 1997, and all survey work used this coordinate system (CA State Plane, NAD 83, Zone 1). Cross section headpins were surveyed with a total station for horizontal location, and cross section pin elevations were surveyed with an engineers level for greater elevational precision. Additionally, the upstream portion of the site was surveyed by total station to develop a Digital Terrain Model (DTM) of the site after each construction phase of the Floodway Rehabilitation Project. Three sets of tracer rocks were placed on cross sections. Four scour cores were installed on two cross sections: two on a coarse lateral bar surface, and two within a straight riffle. Bed material excavated for scour core installation was also sieved for particle size analysis.



Note: Marked rock station location based on distance from the left bank rebar pin.

FIGURE 22. LOWER CLEAR CREEK PELTIER VALLEY BRIDGE GEOMORPHIC STUDY SITE MARKED ROCK AND SCOUR CORE LOCATIONS

12/6/01

A) At Peltier Valley Bridge study site
near cross section #883+25
Scour cores

B) At Peltier Valley Bridge study site
on cross section #885+00
Marked rocks

FIGURE 23. LOWER CLEAR CREEK AT PELTIER VALLEY BRIDGE STUDY SITE
MARKED ROCKS AND SCOUR CORES

12/6/01

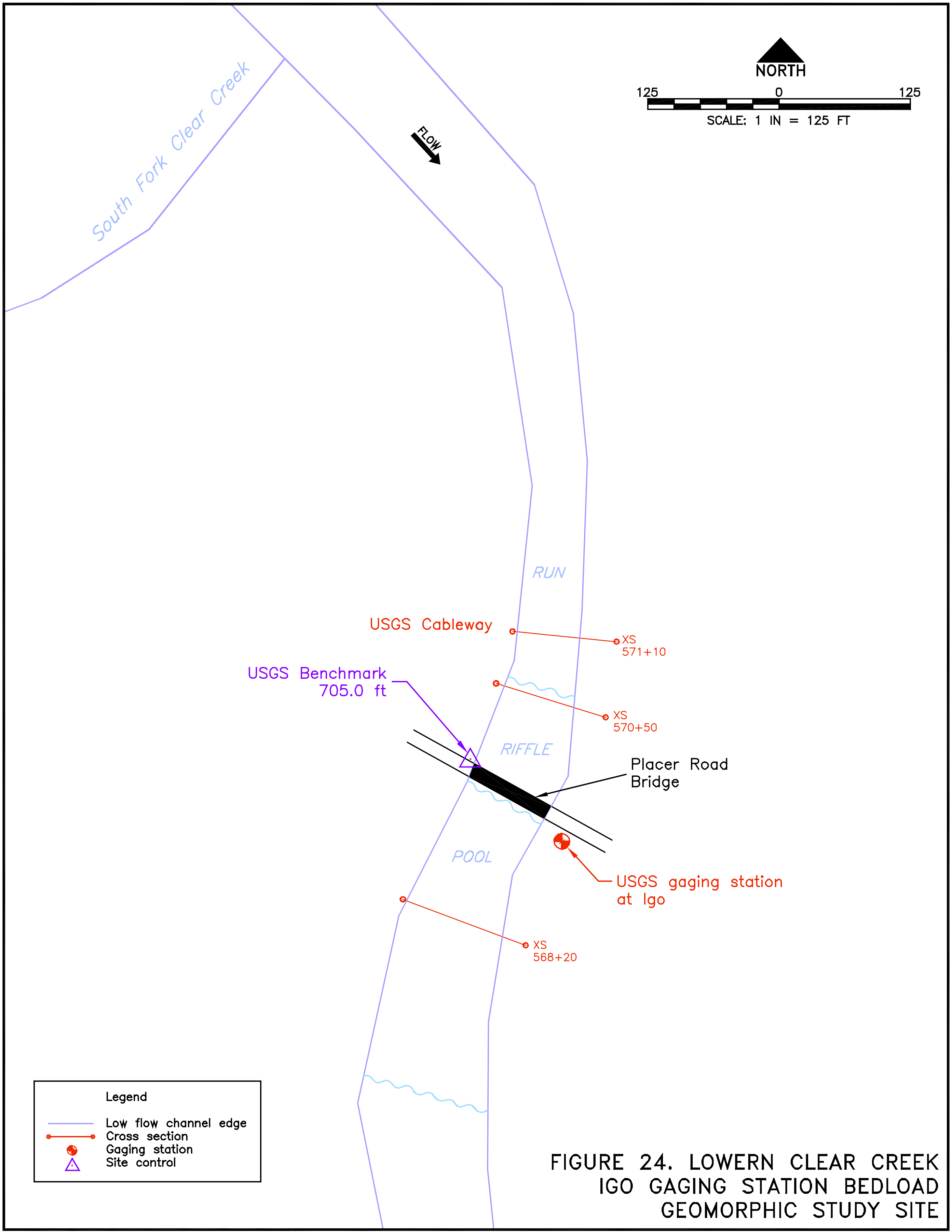
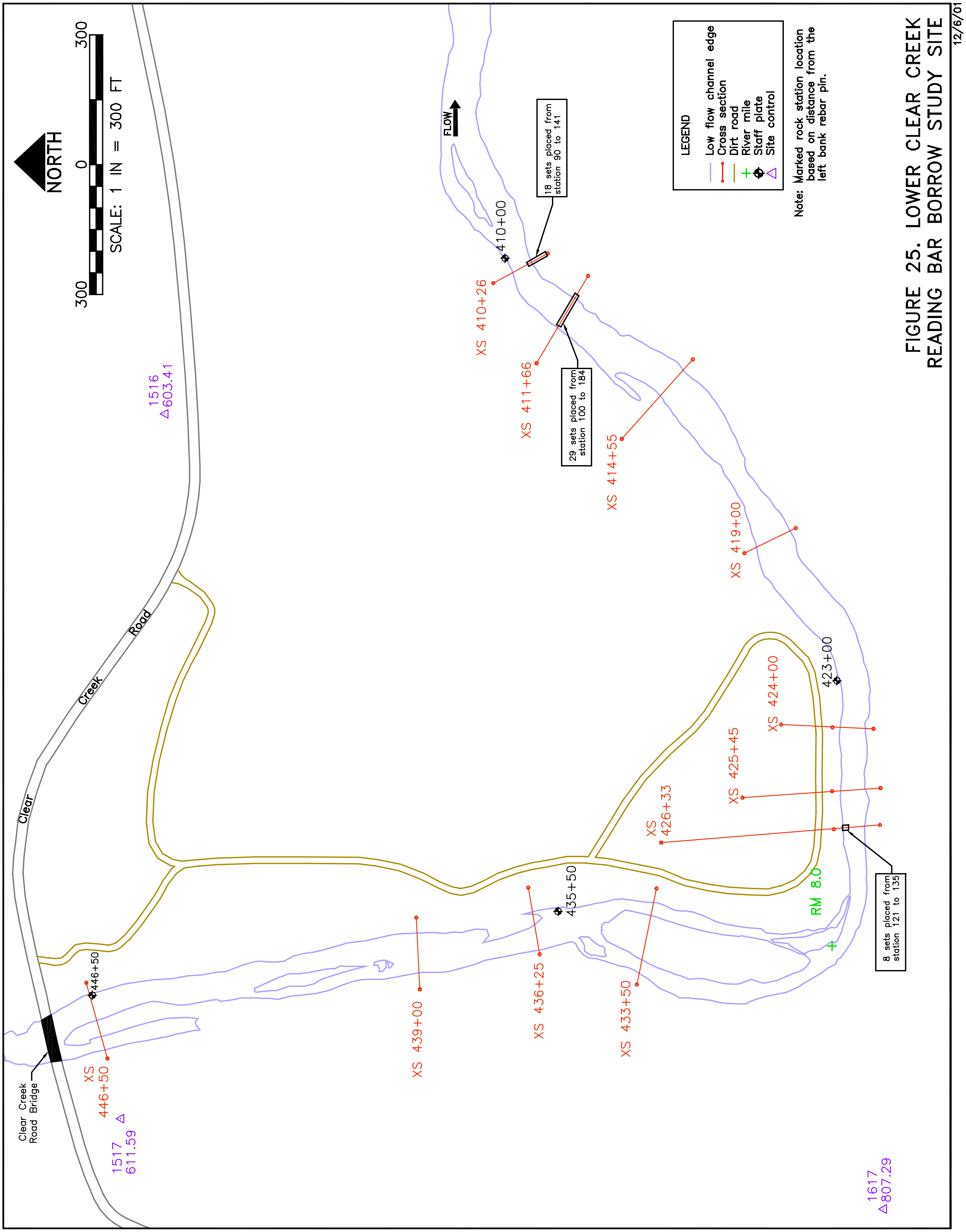


FIGURE 24. LOWERN CLEAR CREEK IGO GAGING STATION BEDLOAD GEOMORPHIC STUDY SITE

12/6/01



Note; Marked rock station location based on distance from the left bank rebar pin.

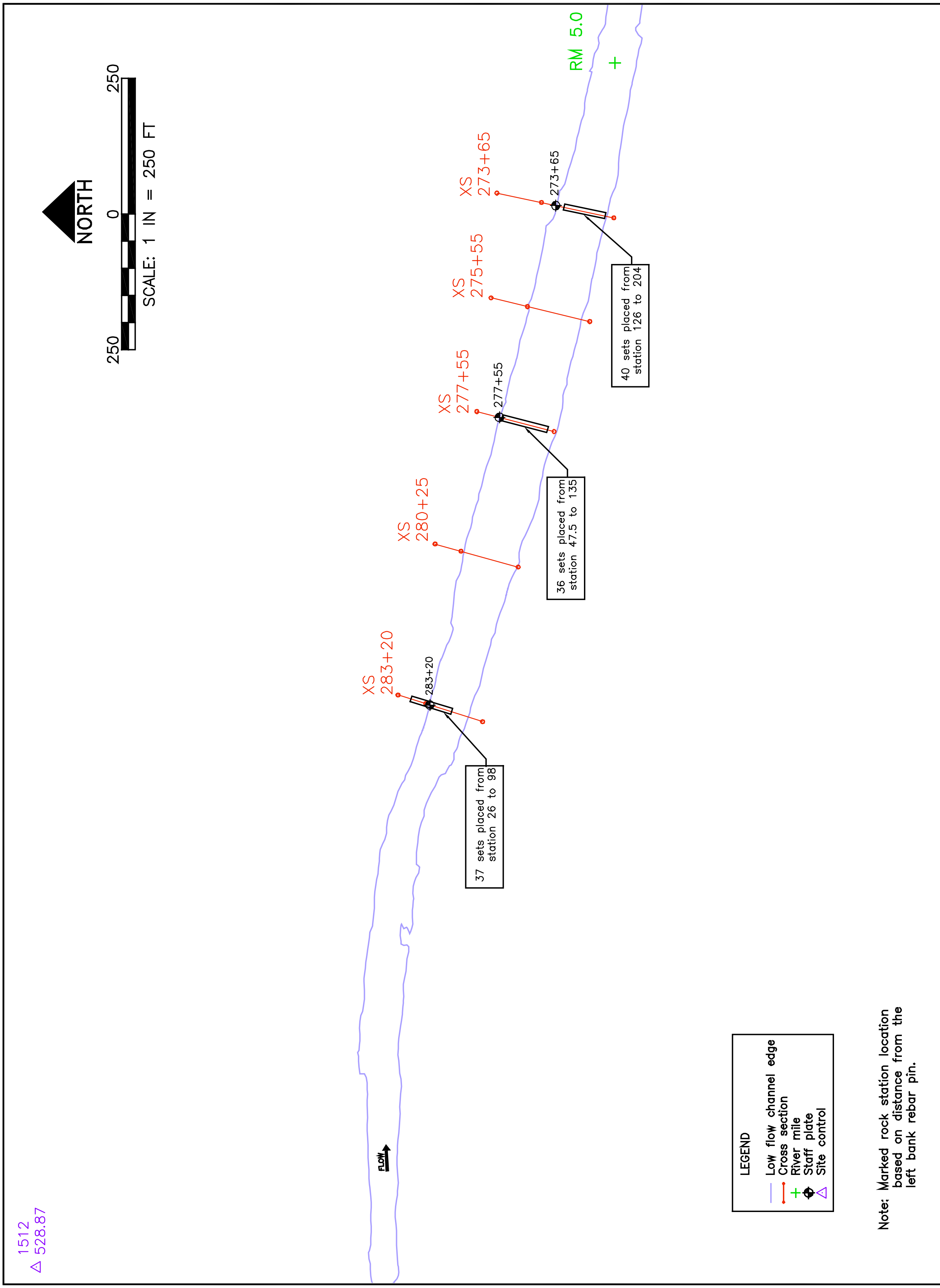
FIGURE 25. LOWER CLEAR CREEK READING BAR BORROW STUDY SITE

4.4. Renshaw Riffle Study Site

The Renshaw Riffle study site is located just downstream of the Saeltzer Dam site in the lower alluvial Reach 4 from RM 5.0 to 5.2, and is approximately 1.2 miles upstream of the Floodway Rehabilitation Project site (Figure 19). A right bank steep bluff and left bank riparian berms confine the reach, and because the reach is a long and straight riffle/run, it is suitable for hydraulic computations and bedload sampling. The reach is also one of the highest concentrations of fall-run chinook salmon spawning on the stream, although the large amount of sand in the spawning gravels makes spawning gravel quality poor. The site was selected for bed mobility and bed scour monitoring, bed mobility modeling, and bedload transport measurements. Five cross sections were installed within a 1,000 ft reach, with vertical control provided by Astro Suveying control point #1512 (elevation = 528.87 ft) on the north side bluff (Figure 26). This vertical control was used to survey cross sections with an engineers level, but the cross sections were located by placing them on aerial photographs rather than GPS or total station surveys from the Astro Surveying control points.

4.5. Floodway Rehabilitation Project

The Lower Clear Creek Floodway Rehabilitation Project is located from RM 2.2 to 3.8, and will be filling instream gravel mining pits to recreate a defined bankfull channel and functional floodplains (Figure 19). The existing channel morphology severely disturbed, but restoration activities will be restoring a more natural channel morphology. We conducted bedload transport modeling in this reach to compare with upstream reaches and to evaluate the channel geometry design. Geometric data for selected cross sections was obtained from the channel designs, and hydraulic data was obtained from a HEC-RAS model run under design geometric conditions at 3,000 cfs.



Note: Marked rock station location based on distance from the left bank rebar pin.

FIGURE 26. LOWER CLEAR CREEK RENSHAW RIFFLE STUDY SITE

12/6/01

5. GEOMORPHIC EVALUATIONS

The geomorphic evaluation of lower Clear Creek was intended to (1) estimate thresholds at which different alluvial features and/or particle sizes are mobilized, (2) estimate thresholds and magnitude of bed scour in different alluvial features, and (3) estimate rates of sediment transport. Our fieldwork employed six general experimental techniques:

1. placing painted tracer rocks on the surface of different alluvial feature types (e.g., exposed gravel bars, pool-tails, riffles) to determine the discharge threshold necessary to mobilize the stream bed surface;
2. modeling high flow hydraulics to predict shear stress and bed mobility thresholds;
3. placing scour cores on discrete alluvial features, to relate the depth of scour of subsurface sediment layers (and subsequent redeposition) to flood magnitude;
4. measuring sediment transport rates using a Helley-Smith bedload sampler, and developing rating curves to empirically estimate coarse sediment transport during the high flow season;
5. modeling bedload transport to allow prediction of bedload transport rates and volumes, and developing rating curves to theoretically estimate coarse sediment transport during the high flow season.
6. estimating coarse sediment storage in Reach 1 and 2 to evaluate existing coarse sediment storage and spawning gravel availability.

In addition to these experimental and modeling approaches, we established cross sections at study sites to monitor changes in bed elevation and develop hydraulic geometry relationships, and to estimate appropriate volumes of coarse sediment introductions at different planform features (e.g., bars, riffles, pool tails). The results of the coarse sediment evaluation are contained in Appendix D; cross section plots are contained in Appendix C.

5.1. Bed Mobility Monitoring

Bed mobility monitoring is an empirical technique where painted rocks are placed in the channel, and opportunistically monitored after discrete high flow events to document whether those particles were mobilized by the flow. Ideally, numerous flows would be monitored, such that a relationship of particle mobility as a function of streamflow magnitude can be generated (Figure 18). Generating these empirical curves is based on high flow events, and the natural distribution of high flows (and drought years) tends to require several years for an adequate number of high flows to occur.

5.1.1. Methods

The purpose of tracer rocks is to determine the range of flow thresholds at which surface particles begin to mobilize. Modified Wolman pebble counts (Leopold 1970) were used to characterize the particle size distribution of the surface substrate of selected alluvial features. Rocks of D_{50} and D_{84} diameter were then collected, painted fluorescent orange, and placed at regular intervals along cross sections traversing the alluvial feature of interest. The D_{50} and D_{84} describe the intermediate axis diameter of a rock that represents the particle size where 50% and 84% of rocks in a given deposit are finer. This results in the D_{50} being the median particle diameter of a given deposit, and the D_{84} representing the larger framework particles of a given deposit. We consider movement of the D_{84} as the criteria for bed mobility for a given deposit since the D_{84} represents the matrix particle (framework) of that deposit. Painted rocks were placed into the bed surface to simulate surrounding substrate conditions, then left for ensuing high flow events. Following a peak discharge capable of mobilizing the bed surface, we returned to monitor tracer rock movement and the distance rocks were transported (if able to recover them downstream). Because different reaches and different alluvial features have unique mobility thresholds, numerous monitoring stations are required. We developed 11 tracer rock experiments at three different sites in Clear Creek from

1998 to 2000, including the Renshaw Riffle, the Reading Bar site, and the Peltier Valley Bridge site (Table 4).

Table 4. Pebble count and marked rock placement summary

Study Site	Cross Section	Station range[1]	# of rock sets	D_{50}	D_{84}
Peltier Valley Bridge	879+00	79 to 88[2]	5	54 mm[4]/ 50 mm[5]	128 mm[4]/ 117 mm[5]
	883+50	20 to 36[2]	9	83 mm[4]/ 87 mm[5]	140 mm[4]/ 143 mm[5]
	885+00	5 to 48[2]	22	79 mm[4]/ 76 mm[5]	152 mm[4]/ 135 mm[5]
	885+00	113 to 130[2]	8	70 mm[4]/ 70 mm[5]	117 mm[4]/ 113 mm[5]
	886+20	106 to 128[2]	12	114 mm[4]/ 110 mm[5]	181 mm[4]/ 176 mm[5]
	891+80	50 to 104[3]	None	126 mm[5]	251 mm[5]
Igo Gaging Station	571+10	40 to 99[3]	None	79 mm[5]	200 mm[5]
Reading Bar	410+26	90 to 141[2]	18	57 mm[4]/57 mm[5]	115 mm[4]/115 mm[5]
	411+66	100 to 184[2]	29	65 mm[4]/ 65 mm[5]	130 mm[4]/ 132 mm[5]
	426+33	121 to 135[2]	8	44 mm[4]/44 mm[5]	76 mm[4]/76 mm[5]
	436+25	On point bar	None	135 mm[5]	215 mm[5]
Renshaw Riffle	273+65	126 to 204[2]	40	38 mm[4]/ 36 mm[5]	93 mm[4]/ 92 mm[5]
	277+55	47.5 to 135[2]	36	28 mm[4]/ 27 mm[5]	68 mm[4]/ 75 mm[5]
	283+20	26 to 98[2]	37	30 mm[4]/ 32 mm[5]	54 mm[4]/ 56 mm[5]

[1] Station range references distance from left bank cross section pin (looking downstream), in feet.
[2] Station range is for marked rock placement; pebble counts were at approximately the same range.
[3] Station range is for pebble counts only since no marked rocks were placed.
[4] Size of marked rock placed, size may be slightly different from pebble count due to field calculation.
[5] Size determined from pebble count, divide by 304.8 to convert to feet.

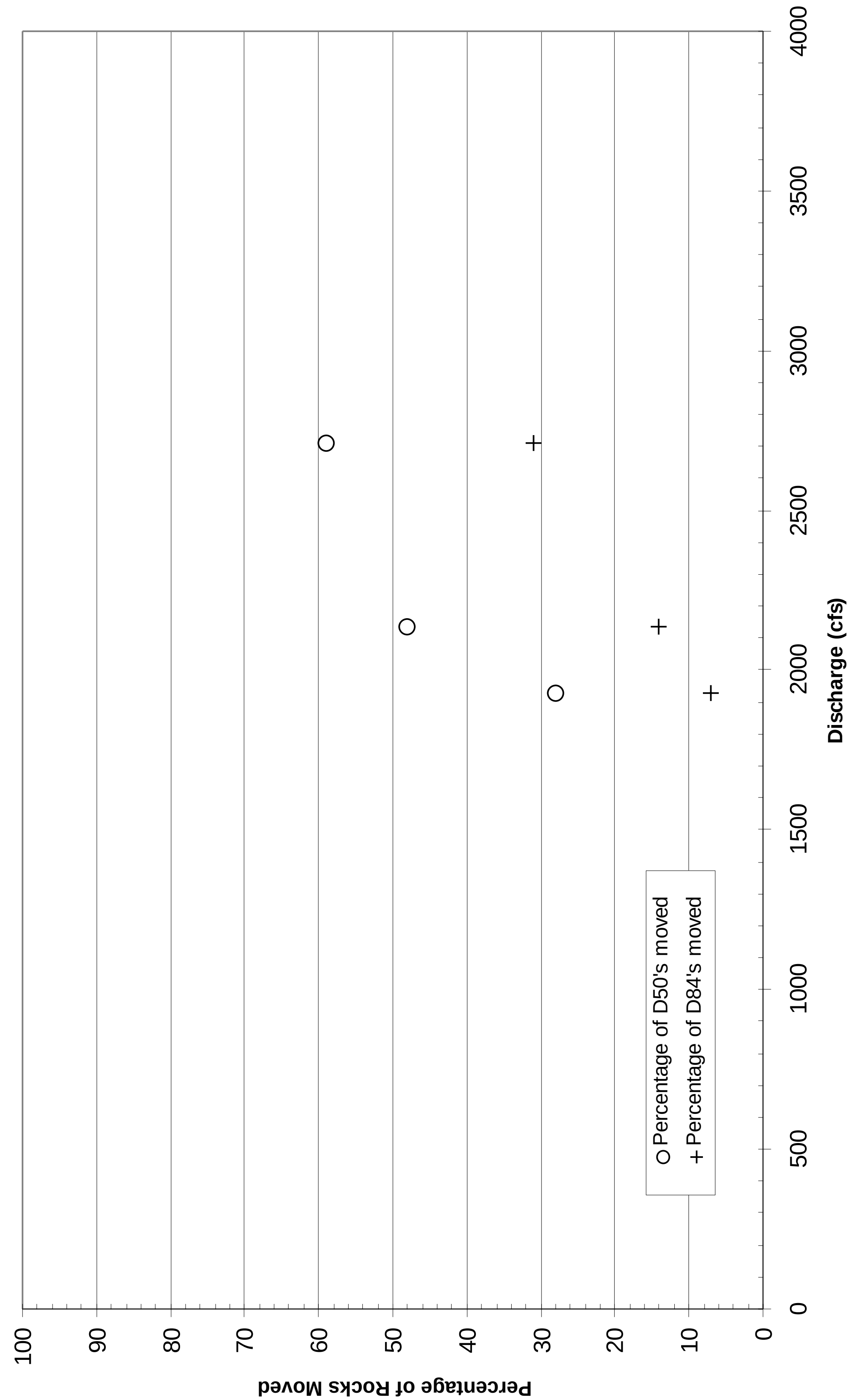
5.1.2. Results

Marked rock and scour core experiments began in December 1998 and continued through winter of 2000, documenting several moderate flood events: during WY1999, peak flows of 1,926 cfs and 2,710 cfs were monitored; during WY2000 a peak flow of 2,134 cfs was observed. Marked rocks were placed on 11 cross sections, several sites only documented surface particle mobility for a single flow (Table 5).

For the same WY2000 flood event (Q=2,082 cfs), tracer rocks at Reading Bar were also mobilized, but much less so than at the Renshaw Riffle. Two cross sections, 410+26 and 411+66, were placed across coarse gravel bar and riffle features, with D_{84}'s from 90 to 115 mm. No rock movement was observed at XS 410+26, and only 14 and 48 percent of D_{84}'s and D_{50}'s respectively, were transported at XS 411+66.

At Reading Bar, a total of two and three peak flow events, respectively, were documented at cross sections 411+66 and 426+33. These data were plotted to show the relationship between discharge and the percentage of surface particles mobilized (Figure 27), and with more data, should follow the conceptual trend shown in Figure 18. At XS 411+66 the discharge of 1,926 cfs (on Jan. 22, 1999) showed little mobilization, but the Feb. 13, 2000 peak flow of 2,124 cfs and February 6 peak flow of 2,710 cfs moved a proportionally higher percentage of tracer rocks, indicating the threshold for surface particle mobility is in the discharge range of approximately 3,000 cfs. At Reading Bar cross section 426+33 traversing an incipient bar forming where riparian berm confinement was previously removed, a tracer rock set was placed from the low water margin out to the edge of the bar near the center of the channel. The Feb 13, 2000 peak event of 2,134 cfs mobilized all D_{50}'s and most (63%) of D_{84}'s. The smaller peak of 750 cfs on

Figure 27. Reading Bar XS 411+66 Marked Rock Movement



Feb 17, 2000 only readjusted two rocks, both D_{50}'s, both located on the outer edge of the incipient bar where mobilization would be expected to initiate.

Table 5. Marked rock observation summary table

Study Site	Cross Section	Type of alluvial deposit	Peak discharge	Discharge date	% D_{50} rock sets moved	% D_{84} rock sets moved
Peltier Valley Bridge	879+00	Inner channel lateral bar and pool tail	250 cfs	9/11/99	0%	0%
	883+50	Inner channel cobble riffle	250 cfs	9/11/99	0%	0%
	885+00	Inner channel lateral bar	250 cfs	9/11/99	0%	0%
	885+00	Dry portion of large point bar	250 cfs	9/11/99	0%	0%
	886+20	Large cobble pool tail	250 cfs	9/11/99	0%	0%
Reading Bar	410+26	Large cobble point bar	2,134 cfs	2/13/00	0%	0%
	411+66	Large cobble riffle	1,926 cfs	1/22/99	28%	7%
	411+66	Large cobble riffle	2,710 cfs	2/6/99	59%	31%
	411+66	Large cobble riffle	2,134 cfs	2/13/00	48%	14%
	426+33	Lateral gravel bar	750 cfs	2/17/99	0%	0%
	426+33	Lateral gravel bar	2,134 cfs	2/13/00	100%	63%
Renshaw Riffle	273+65	Cobble riffle	2,134 cfs	2/13/00	78%	40%
	277+55	Cobble riffle	2,134 cfs	2/13/00	75%	44%
	283+20	Cobble riffle	2,134 cfs	2/13/00	92%	100%

* peak discharges obtained from CDEC website, and may be slightly different than USGS values

The Peltier Bridge site monitoring cross sections were surveyed and marked rocks installed during Nov. 1999. Because the site is immediately downstream of Whiskeytown Dam, flows did not exceed 250 cfs during our monitoring period. Therefore we were not able to collect any bed mobility data at this site.

In summary, Water Year 1999 and 2000 were dry water years. Monitoring of additional high flow events at these sites would improve our bed mobility threshold estimates. In the absence of additional monitoring, the marked rock data suggests that flows exceeding 3,000 cfs are needed to mobilize the riffle bed particles in most portions of Reaches 3A and 4, and flows greater that 2,000 cfs to begin mobilizing more mobile gravel deposits. At Renshaw Riffle, the flow threshold appears to be much lower than the other sites monitored (approximately 2,000 cfs), but additional study sites are needed to confirm this.

5.2. Bed Mobility Modeling

Bed mobility modeling is often used in place of empirical measurements (marked rocks) when lack of time or high flows prohibits empirical techniques. Bed mobility modeling is a two step process: First, a bed mobility model is used to predict the force needed to mobilize a particle size of interest, and second, a hydraulic model or computation is needed to relate that force to a streamflow magnitude. We typically use both modeling and empirical approaches to ensure that we have some capability to estimate streamflow thresholds that begin to mobilize the bed surface. We prefer and trust empirical results much more than modeling results. If our study is conducted during a wet water year that provides empirical measurements, we rely more on those observations than our modeling results.

5.2.1. *Methods*

The purpose of bed mobility modeling is to predict the streamflow discharge (via shear stress) that begins to mobilize particles in a certain gravel deposit. Bed mobility modeling can often provide an estimate of discharge necessary to mobilize the bed, provided uniform flow conditions exist (to improve the hydraulic model's prediction of shear stress, of which bed mobility is dependent). On Clear Creek, we applied a bed mobility model at the USGS Igo Gaging Station XS 1+10 (RM 10.1), Reading Bar XS 411+66 (RM 7.6), Renshaw Riffle XS 277+55 and 283+20 (RM 5.1), and the Floodway Rehabilitation Project (RM 2.2 to 3.8). At three of these sites, we input cross section data into a HEC-RAS model to predict main channel boundary shear stress as a function of discharge. These sites were installed in long straight riffles where simplifying uniform flow assumptions between flow and shear stress can be reasonably made; other study sites were too complex to make this simplifying assumption and were not modeled. In the case of the USGS Igo Gaging Station site, we monitored water surface elevations and slope to predict shear stress as a function of discharge rather than applying a hydraulic model. We next applied the Shields Equation (Equation 1) to predict the shear stress necessary to mobilize the particle size of interest (in our case, the D_{84} of the riffle surface) at all site.: The boundary shear stress necessary to achieve this reference dimensionless shear stress assumed to signify a mobilized bed is computed from:

$$\tau_b = \tau^*_{ri}\left(\rho_s - \rho_w\right) g D_i \tag{1}$$

where D_i= the particle size of interest (D_{84}), ρ_s=density of sediment (165 lb/ft^3), ρ_w=density of water (62.4 lb/ft^3), and g=gravitational acceleration (32.2 ft/s^2). The critical Shields Parameter, τ^*_{ri}, is a reference dimensionless shear stress of low but measurable sediment transport rate (used to approximate bed mobilization). To compute the boundary shear stress necessary to mobilize a given D_{84}, the value of critical Shields Parameter needs to be estimated. Critical Shields Parameter values of 0.02 to 0.025 are often used for D_{84} particle sizes of low gradient alluvial rivers, or a bed mobility model can be applied to predict critical Shields Parameter for the D_{84} particle. When using both marked rocks and applying various bed mobility models to compare observed versus predicted results, we have found that the Andrews (1994) bed mobility model reasonable predicts bed mobility thresholds:

$$\tau^*_{ri} = 0.0384\left(\frac{Di}{D_{50}}\right)^{-0.887} \tag{2}$$

where D_i= the particle size of interest (again, we prefer to use the D_{84} particle of a bar surface to signify total mobility of the bar) and τ^*_{ri} is a reference dimensionless shear stress of low but measurable transport rate (used to approximate bar mobilization). Andrews found that as D_i increases towards the D_{84} particle size, the critical Shields Parameter reaches an asymptotic value of 0.02; this limitation has been applied to this relationship, such that critical Shields Parameter predicted by Equation 2 is not allowed to be smaller than 0.02. The discharge necessary to achieve the critical boundary shear stress (τ_b) in Equation 1 can be simply interpreted from the streamflow discharge to shear stress output from the hydraulic model (or measurements in the case of the Igo Gaging Station site).

5.2.2. *Results*

The streamflow discharge versus shear stress curves were computed for all modeling sites, and these curves were then used to evaluate the discharge necessary to exceed the computed critical boundary shear stress values from Equation 1 (Table 6).

With the exception of the Renshaw Riffle study site, these results suggest that that riffles do not tend to mobilize until streamflows exceed approximately 3,000 cfs to 3,500 cfs. These results are consistent with marked rock experiments at XS 411+66 (31% D_{84}'s mobilized by 2,700 cfs) and the bedload transport measurements at XS 571+10 (very small transport rates of small gravels at 3,200 cfs, described in following section). The Renshaw Riffle is a very unique site, due to a geologic gradient control that results in a very low gradient (0.0006) compared to the majority of Reaches 3A and 4 (0.0023 to 0.0034). The particle size has responded to this lower gradient and is approximately half the size of particles in adjacent reaches. The modeling results at the Renshaw Riffle predict mobility at flows greater than 1,100 cfs, and marked rock observations at XS 283+20 (100% mobilized by 2,134 cfs) may support this modeling prediction.

Table 6. Bed mobility modeling results.

Study Site	Cross Section	D_{50}	D_{84}	Critical Shields Parameter	Critical boundary shear stress	Predicted discharge to mobilize D_{84} particles
Igo Gaging Station	571+10	79 mm	200 mm	.020	1.33 lb/ft^2	3,400 cfs
Reading Bar	411+66	65 mm	130 mm	.021	0.91 lb/ft^2	3,500 cfs
Renshaw Riffle	277+55	27 mm	75 mm	.020	0.51 lb/ft^2	1,700 cfs
	283+20	32 mm	56 mm	.023	0.44 lb/ft^2	1,100 cfs
Floodway Rehabilitation Project	Typical	34 mm	100 mm	.020	0.68lb/ft^2	3,100 cfs

5.3. Bed Scour Monitoring

Bed scour monitoring is an empirical approach that attempts to quantify bed scour and redeposition during flows that greatly exceed bed mobility thresholds. During the rising limb of a flood hydrograph, the bed surface begins to mobilize, and as discharge continues to increase, deeper mobilization (scour) begins to occur. If the stream is in a reasonable sediment balance (Attribute 5), redeposition on the receding limb of the flood hydrograph will restore some or all of the depth scoured on the ascending limb. Geomorphically and ecologically, bed scour and redeposition is an important process for a variety of functions, including scouring/redepositing salmonid spawning gravels, scouring riparian seedlings along the low flow channel margin that may eventually fossilize gravel bars, and reducing embeddedness on the stream bottom and channel margins. One important point should be made to clarify a common misconception of “Flushing Flows”. Flushing flows are often described as flow releases that mobilize and/or scour the bed surface in order to “flush” fine sediment out of the gravels, usually inferring a biological benefit from reducing fine sediment storage in spawning gravels. What is often neglected is that mobilizing and/or scouring the bed surface is only one component of a successful “flushing flow”; fine sediment supply from upstream sources must also be reduced in order for this approach to work. For example, the bed may scour during the ascending limb of the hydrograph (exposing and mobilizing fine sediments in the bed surface), but unless upstream fine sediment supply is reduced, the redeposited material will include a similar contribution of sand, resulting in no net change in gravel quality.

5.3.1. Methods

Scour chains (Lisle and Eads, 1991) and scour cores (McBain and Trush, 1997) are the two common field methods used to monitor bed scour. We have found that scour cores tend to provide more reliable results and are usually more recoverable after a large flood event, so we used them in this evaluation. Modeling efforts to predict local bed scour are problematic because of the complex nature of the local hydraulics that cause bed scour during flood flows (Hales, 1998), so we rely on empirical methods rather than modeling methods. However, empirical methods require high flow events to provide any monitoring data, and in the absence of managed flood releases from a dam, we rely on natural floods to provide monitoring data. The drawback with this approach is that there is a significant likelihood that a meaningful flood event will not occur during a short study period, resulting in little or no data being collected.

As with bed mobility thresholds, bed scour relationships vary considerably in different alluvial deposits and different planform locations (e.g., point bars versus pool tails). Scour cores are typically placed in spawning riffles, pool tails, and other finer-grained features by excavating subsurface sediments with a 8-inch or 12-inch diameter stainless steel cylinder to a minimum depth of one foot, then backfilling the excavation with appropriately sized painted gravels. The painted gravels are generally no larger than the D_{50} to ensure their mobilization along with the surrounding bed. The bottom of the excavated core and the top of the backfilled core are both surveyed with engineer level to document elevation, and the exact position within the stream is established either by cross section station or by triangulating the position from known points. Following the flood recession, the scour core position is relocated, the undisturbed bed surface resurveyed, then the surface layer is removed until the painted tracer rocks are re-exposed. This surface is also resurveyed, then compared to the originally placed scour core elevation and the undisturbed post-flood surface, to compute the depth of scour and depth of re-deposition, respectively (Figure 28). Similar to tracer rock experiments, the data are plotted as scour depth verses discharge to develop a rating curve. The rating curve thus indicates discharge thresholds for scour, and scour depth. We placed scour cores on more mobile alluvial features within the Clear Creek channel at the Renshaw Riffle study site, Reading Bar study site, and Peltier Valley Bridge study site (Table 7).

5.3.2. Results

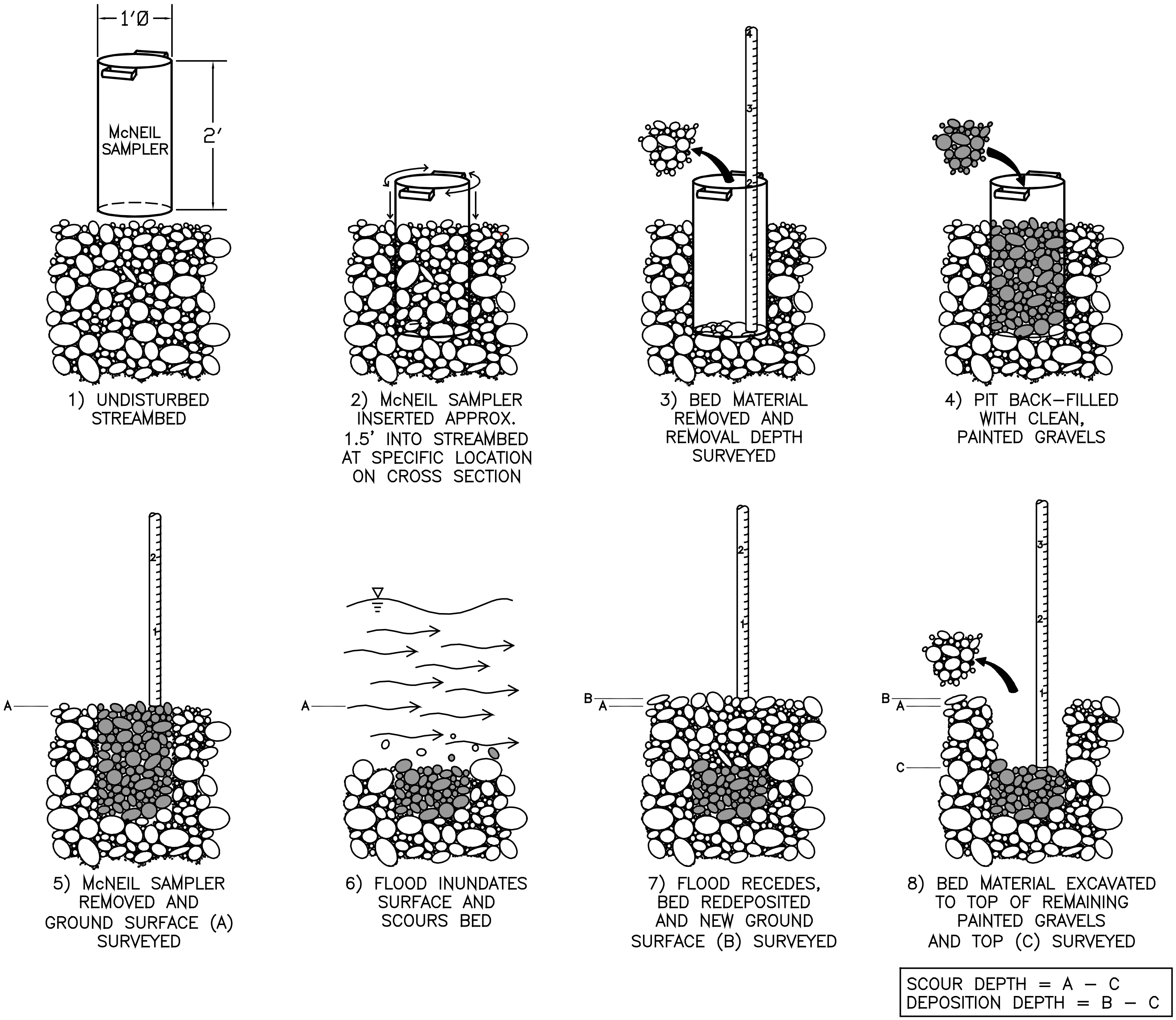
The Reading Bar scour cores on XS 410+26 were placed on the right bank point bar in coarse substrates (large cobbles) in March 1999, and were subjected to peak discharges of 1,378 cfs, 1,522 cfs, and 2,134 cfs, none of which inundated the bar with adequate depth to cause scour. Fine sediment has deposited on the bar surface, and had become heavily vegetated due to the fine sediment deposition and lack of scouring flows. At Reading Bar XS 426+33, scour cores were placed on an incipient left bank bar (medium to large gravels) forming where bank riparian berm confinement had previously been mechanically removed as part of the Floodway Rehabilitation Project. The scour cores on XS 426+33 documented scour and subsequent deposition of approximately 0.2 ft during a peak flow of 2,134 cfs. This small amount of “scour” reflects a marginal surface mobilization rather than meaningful bed scour. No other peak flow events have been large enough to initiate bed scour at this monitoring location.

At the Renshaw Riffle cross sections 273+65 and 277+75, peak events of 1,378 cfs and 2,134 cfs caused scour ranging from 0.25 ft to 0.4 ft at four scour core locations, with virtually no redeposition at these scour core locations. As with the Reading Bar XS 426+33 site, this small amount of “scour” is functionally a surface mobilization of the bed surface, which corroborates marked rock observations at the site. This entire riffle reach has exhibited fairly dynamic bed elevation changes resulting from both scour and from chinook salmon spawning, although the scour results are a result of the flows rather than a result of salmon spawning. As discussed in the preceding bed mobility sections, particle size distribution at Renshaw Riffle is smaller than most other reaches, and gravels are less consolidated due to high intensity and concentration of salmon spawning over the years.

The Peltier Valley Bridge study site did not experience any flows greater than 250 cfs over the monitoring period, so we were not able to provide any bed mobility or scour estimates in Reach 1.

5.4. <u>Bedload Transport Measurements</u>

The purpose of bedload transport measurements is to estimate the rate of coarse sediment transported at different discharges. This relationship can then be used to construct a bedload transport rating curve that allows prediction of coarse sediment transported at unmeasured flows, and annual sediment yield (total



1) UNDISTURBED STREAMBED

2) McNEIL SAMPLER INSERTED APPROX. 1.5' INTO STREAMBED AT SPECIFIC LOCATION ON CROSS SECTION

3) BED MATERIAL REMOVED AND REMOVAL DEPTH SURVEYED

4) PIT BACK-FILLED WITH CLEAN, PAINTED GRAVELS

5) McNEIL SAMPLER REMOVED AND GROUND SURFACE (A) SURVEYED

6) FLOOD INUNDATES SURFACE AND SCOURS BED

7) FLOOD RECEDES, BED REDEPOSITED AND NEW GROUND SURFACE (B) SURVEYED

8) BED MATERIAL EXCAVATED TO TOP OF REMAINING PAINTED GRAVELS AND TOP (C) SURVEYED

SCOUR DEPTH = A – C
DEPOSITION DEPTH = B – C

FIGURE 28. SCOUR CORE INSTALLATION AND MONITORING PROCEDURE

12/19/01

Table 7. Scour core observation summary table.

Site	Cross section	Type of alluvial deposit	Peak Discharge	Date of Flow	Cross Section Station*	Net Scour	Net Deposition
Peltier Bridge							
	879+00	Floodplain bar	250 cfs	2/13/00	Triangulated (F)	0.0 ft	0.0 ft
	883+25	Lg. gravel pool tail	250 cfs	2/13/00	Triangulated (B)	0.0 ft	0.0 ft
	883+25	Lg. gravel pool tail	250 cfs	2/13/00	Triangulated (C)	0.0 ft	0.0 ft
	883+25	Lg. gravel pool tail	250 cfs	2/13/00	Triangulated (D)	0.0 ft	0.0 ft
	883+25	Lg. gravel pool tail	250 cfs	2/13/00	Triangulated (E)	0.0 ft	0.0 ft
	886+20	Gravel lee deposit	250 cfs	2/13/00	161.5 (A)	0.0 ft	0.0 ft
Reading Bar							
	410+26	Lg. cobble point bar	2,134 cfs	2/13/00	103.6	0.0 ft	0.0 ft
	410+26	Lg. cobble point bar	2,134 cfs	2/13/00	118.5	0.0 ft	0.0 ft
	426+33	Lateral gravel bar	2,134 cfs	2/13/00	421.6	-0.16 ft	0.16 ft
	426+33	Lateral gravel bar	2,134 cfs	2/13/00	427.6	-0.21 ft	0.11 ft
Renshaw Riffle							
	273+65	Cobble riffle	1,378 cfs	3/24/99	148	-0.36 ft	0.0 ft
	273+65	Cobble riffle	1,378 cfs	3/24/99	168	0.0 ft	0.0 ft
	273+65	Cobble riffle	1,378 cfs	3/24/99	188	-0.46 ft	0.0 ft
	273+65	Cobble riffle	2,134 cfs	2/13/00	148	0.0 ft	0.0 ft
	273+65	Cobble riffle	2,134 cfs	2/13/00	168	0.0 ft	0.0 ft
	273+65	Cobble riffle	2,134 cfs	2/13/00	188	-0.35 ft	0.0 ft
	277+55	Cobble riffle	1,378 cfs	3/24/99	66	0.0 ft	0.0 ft
	277+55	Cobble riffle	1,378 cfs	3/24/99	86	0.0 ft	0.0 ft
	277+55	Cobble riffle	1,378 cfs	3/24/99	106	-0.08	0.0 ft
	277+55	Cobble riffle	2,134 cfs	2/13/00	66	-0.02	0.0 ft
	277+55	Cobble riffle	2,134 cfs	2/13/00	86	-0.25	0.0 ft
	277+55	Cobble riffle	2,134 cfs	2/13/00	106	0.0 ft	0.0 ft

*stationing is feet from left bank cross section headpin

volume of sediment transported annually) based on the transport rating curve and the annual hydrograph can be computed. These measurements can also provide useful information on what streamflows bedload begins to mobilize, helping identify bedload transport thresholds at the measurement location. A suitable empirical bedload transport relationship typically requires several winter high flow periods to sample the full range of flows capable of transporting coarse sediment, and is also largely opportunistic to natural flood events if large dam releases cannot be provided (as was the case for our evaluation). This portion of the study was initiated in 1998, and two moderate flows occurred in 1998 where we could sample bedload transport. From 1999-2001, dry conditions did not provide flows greater than that sampled in 1998, so no further sampling was conducted.

Specific objectives of bedload sampling include:
(1) estimate the discharge at which incipient transport of coarse sediment occurs,
(2) document the particle size distribution of bedload

(3) develop a discharge vs. transport relationship for coarse sediment smaller than 2 mm
(4) develop a discharge vs. transport relationship for coarse sediment larger than 2 mm
(5) develop relationship between flow and cross section-averaged shear stress
(6) calibrate bedload transport formula(s) using measured bedload transport and shear stress measurements.
(7) estimate fine and coarse bedload transport for WY 1998 and 1999 based on transport formula fitted to measured data

5.4.1. Methods

Bedload transport measurements were conducted at the USGS Clear Creek near Igo gaging station cableway (XS 571+10). This site was selected based on (1) the reasonably good hydraulic conditions at this site, (2) the availability of long-term streamflow data, which are necessary to estimate annual sediment yield, (3) the location upstream of the Saeltzer Dam site (sites downstream of Saeltzer Dam would not be representative of bedload transport rates once Saeltzer Dam was removed), and (4) the location near the transition from canyon to alluvial reach would represent the volume of bedload entering the alluvial reach.

Samples were collected on January 14, 1998 and February 9, 1998 during flows of 2,610 cfs and 3,215 cfs respectively. We also attempted to sample on February 7, 1998 during flows exceeding 7,000 cfs, but woody debris and high water velocities made conditions too unsafe to sample. Samples were collected using a Helley-Smith bedload sampler with a six-inch square orifice using standard protocols (Edwards and Glysson, 1988). During the January 1998 measurement, a single sampling pass was conducted from the old Placer Road Bridge, during the rising limb of the hydrograph. Sampling verticals were spaced five feet apart. Hydraulic conditions at the bridge were not favorable, however, due to high velocities and turbulence from the bridge piers. We moved our measurement location approximately 200 ft upstream to the USGS cableway for the February 1998 measurement, where hydraulic conditions were not influenced by the bridge and velocities were much more uniform across the channel. Two sample passes were collected from a cataraft, with sampling verticals spaced five feet apart. In both sampling events, the Helley-Smith sampler was lowered to the bed surface for 60 seconds to collect sediment in transport. The sampler was then raised, the sediment removed from the sampler, and stored for later analysis.

Samples were oven-dried, sieved and weighed by half-phi size classes to determine the particle size distribution for each sample. Individual passes from each measurement were combined and averaged to yield total bedload transport rates for each flow sampled. Transport rates for size fractions larger than 8 mm, smaller than 8 mm, and smaller than 2 mm were also computed so that other bedload transport equations could be fit to the data. Data were then plotted as a function of instantaneous discharge at the time of measurement.

The different particle size classes were analyzed independently for two reasons. First, some bedload equations ignore the finer components of bedload (primarily sand) because transport rates are a function of supply (supply limited) rather than hydraulic competence (transport limited). In other words, because fine sediment has such a fast travel time and is mobilized by moderate flows, the transport rate is dependent on the supply of fine sediment transport rather than hydraulic conditions. Additionally, one objective of future sediment management may be to estimate background coarse sediment input by the watershed, to determine the volume of artificially placed coarse sediment needed to supplement natural input rates.

With only two bedload samples, predicting bedload transport is difficult beyond the range of flows measured; however, our hydraulic data enabled us to fit bedload transport function to the two data points to allow extrapolating to higher discharges. To compute the hydraulic conditions at a variety of discharges, we first surveyed the USGS cableway cross section and measured 1997 and 1998 water surface slopes through the cross section at a variety of high flow events up to 12,800 cfs. The cross section and water surface slopes were used to estimate average boundary shear stress over the effective width of the channel, using the following equation:

$$\tau_b=\rho_w gRS \tag{3}$$

where ρ_w=density of water (62.4 lb/ft^3), and g=gravitational acceleration (32.2 ft/s^2), R= hydraulic radius over the effective width of the channel, and S = energy slope, approximated by the water surface slope under steady, uniform flow conditions. Effective width is defined as that portion of the channel where bedload is typically transported. The hydraulic radius is the cross sectional area divided by the wetted perimeter, with area and wetted perimeter each computed over the effective width of the channel. Field observations during high flows suggested that steady, uniform flow conditions are rare in the rugged Clear Creek canyon, but the USGS cableway sampling location was the best location available. Therefore, an approximation of boundary shear stress using Equation 3 is considered reasonable at our sampling cross section. We related slope to discharge over a wider range of discharge values by fitting a regression curve to our slope measurement data.

The two measured bedload transport data points were then plotted as a function of discharge as follows. Bedload transport of particles coarser than 2 mm were plotted and fit to the Parker (1979) bedload transport relationship (as simplified by Wilcock 1997),

$$Q_b = 0.05798W(\tau_b)^{1.5}\left[1-0.85\frac{\tau_{ref}}{\tau_b}\right]^{4.5} \tag{4}$$

where W = the effective width of channel (63 ft), τ_b = cross sectionally averaged boundary shear stress computed from Equation 3, and τ_{ref} is the cross sectionally averaged boundary shear stress upon which a small but measurable rate of bedload transport occurs. We estimated τ_{ref} by iteratively adjusting the value until the bedload transport curve fit our two data points. Particles finer than 2 mm (fine sediment) were plotted and fit to a power function regression curve. These curves were then extrapolated to higher discharges up to 13,000 cfs. Bedload transport flux for water years 1998-2000 was computed by: 1) computing shear stress for each one-hour average streamflow discharge value obtained from USGS, 2) applying these shear stress values into Equation 4 to compute bedload transport rate for that hour, and 3) summing hourly transport rates for the entire water year.

5.4.2. Results

A secondary objective of bedload transport measurement was to estimate a flow threshold that initiated coarse sediment transport. Our sampling suggested that 3,215 cfs was very close to this threshold (Table 8). The 2,610 cfs flow was transporting predominately sand, whereas the 3,215 cfs flow began transporting medium-sized gravels. Particles slightly greater than 32 mm were being transported by the 3,215 cfs flow, but we did not sample any particles larger than 11 mm during the 2,610 cfs flow. Similarly, the D_{84} in transport for the 3,215 cfs flow and 2,610 cfs flow was 7.5 mm and 1.8 mm, respectively. Therefore, our initial estimate of the threshold for initiation of coarse sediment transport at the Igo Gaging Station is in the 3,000 cfs to 4,000 cfs range.

The sampling cross section and water surface slopes at a variety of high flows are illustrated in Figures 29 and 30, and pertinent hydraulic data are summarized in Table 9.

Figure 29. Igo Gaging Station bedload modeling reach cross section 571+10 at the USGS Gaging Station Cableway

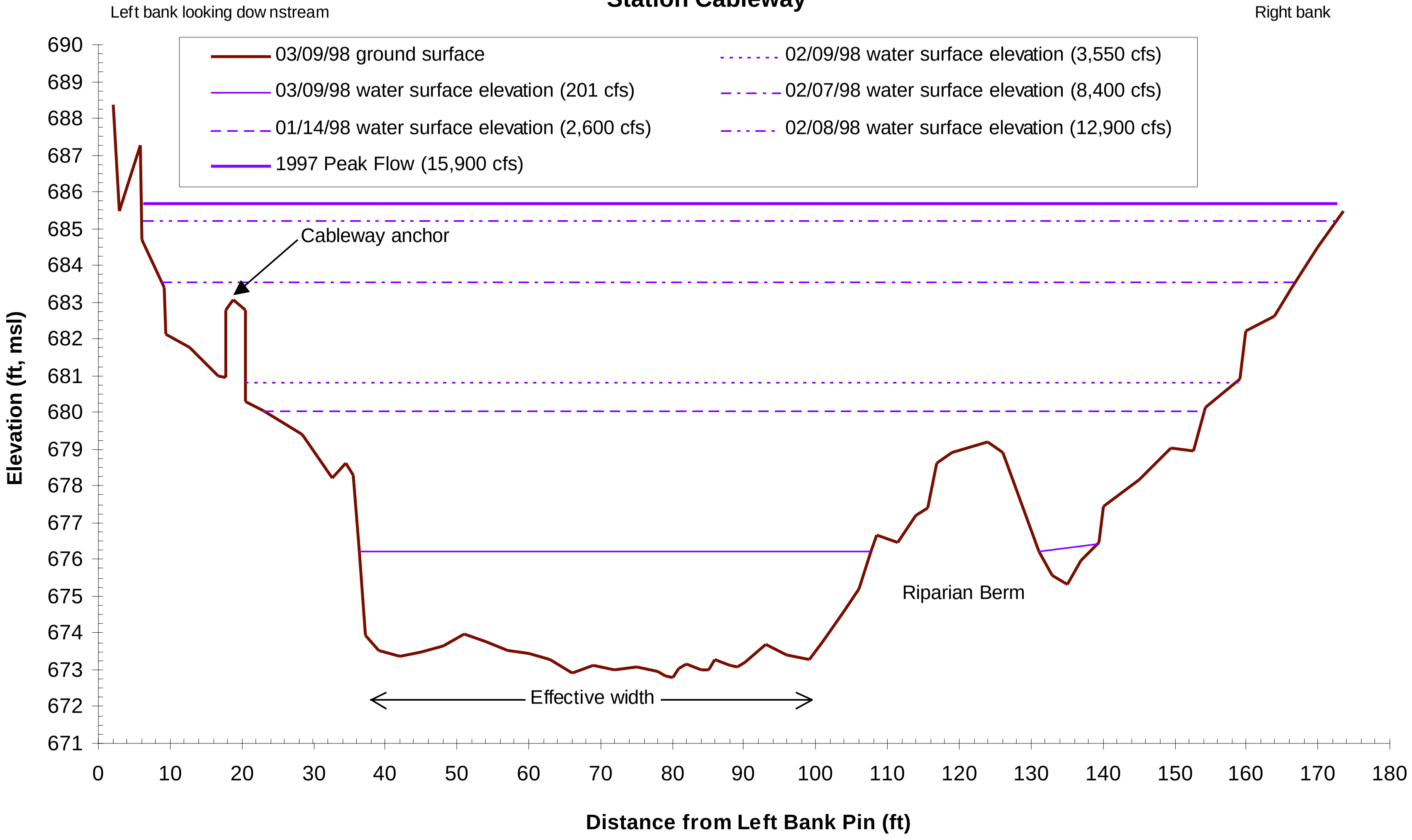


Figure 30. Surveyed water surface profiles through USGS gaging station cableway reach

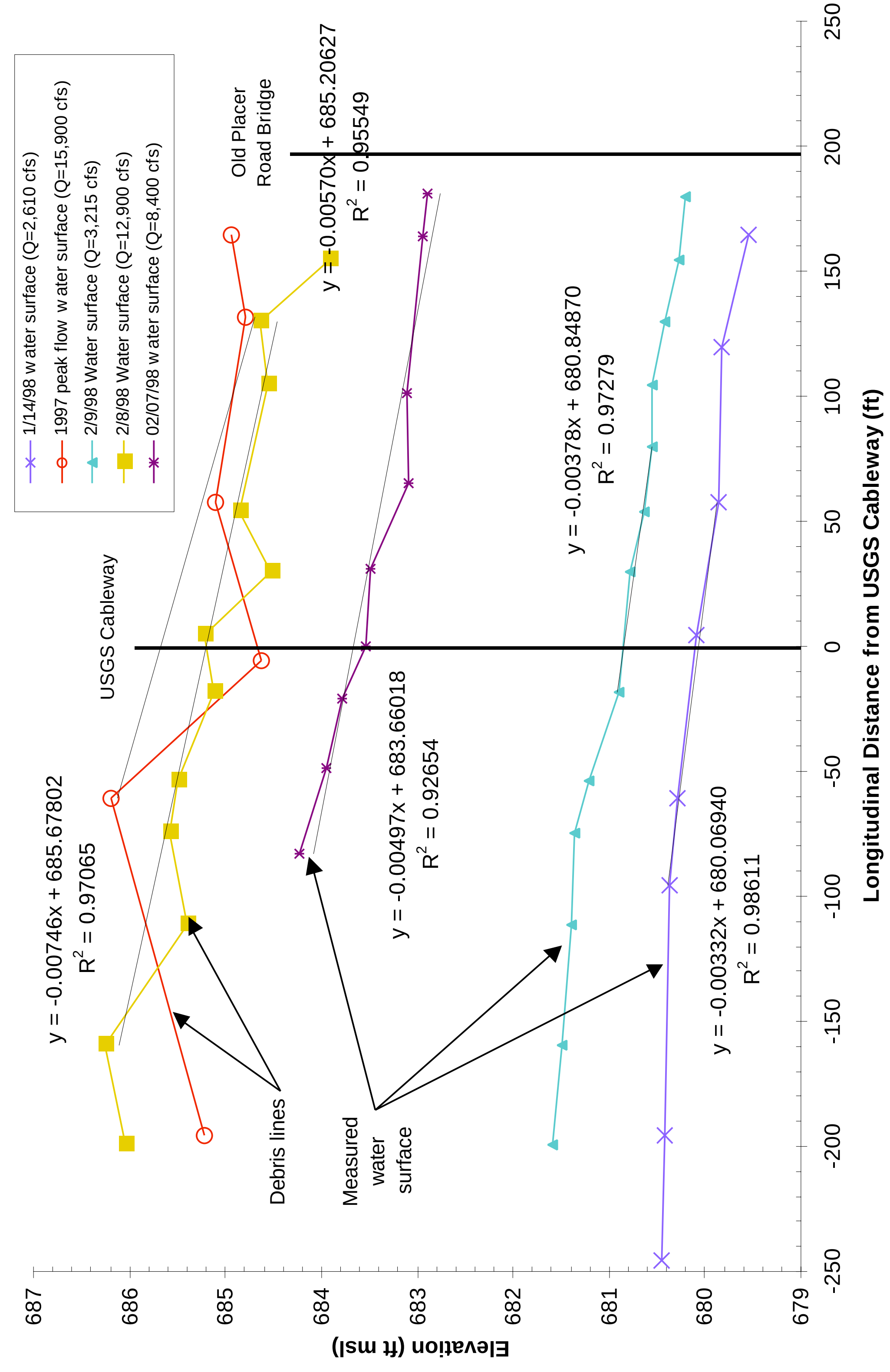


Table 8. Summary of 1998 bedload sampling results at the Igo Gaging Station.

Date	Discharge (cfs)	Passes	Verticals	Sampling time per vertical (seconds)	Bedload D_{84} (mm)	Bedload D_{50} (mm)	Total transport rate (tons/day)	Transport rate > 2 mm (tons/day)	Transport rate < 2 mm (tons/day)
1/14/98	2,610	1	6	60	1.8	1.0	22.5	2.3	20.2
2/7/98	8,400	SAMPLING ABORTED DUE TO UNSAFE SAMPLING CONDITIONS							
2/9/98	3,215	2	12	60	7.5	2.1	117.4	61.0	56.4

Table 9. Summary of pertinent hydraulic variables collected during high flow events in WY 1998. “Average” values depicted in **(a)** represent conditions if the entire cross section is used, whereas “effective” values depicted in **(b)** represent conditions if only that portion of the cross section where bedload transport occurs is used. We used effective width **(b)** in our computations.

Discharge cfs	Slope ft/ft	Average Hydraulic Radius (ft)	Average Shear Stress (lbs/ft^2)
2,600	0.00332	4.47	0.92
3,550	0.00378	4.74	1.12
8,400	0.00497	6.61	2.05
12,900	0.0057	7.79	2.77
15,900	0.00746	8.14	3.79

(a)

Discharge (cfs)	Slope (ft/ft)	Average Hydraulic Radius (ft)	Effective Shear Stress (lbs/ft^2)
2,600	0.00332	5.51	1.14
3,550	0.00378	6.01	1.42
8,400	0.00497	7.62	2.37
12,900	0.0057	8.51	3.03
15,900	0.00746	8.75	4.08

(b)

Because the Parker (1979) relationship requires shear stress as the primary input variable rather than streamflow discharge, a relationship between shear stress and streamflow discharge was developed from our measurements in order to use the Parker relationship. Numerous water surface elevations and slopes were surveyed during high flows in 1997 and 1998 (Figure 30). The largest discharge value was one year old flood debris from the January 1997 flood, and the decay of the debris caused much less accurate stage and slope estimates than those where we actually measured the water surface profiles. Therefore, the regression shown in Figure 31 excluded the 1997 data point.

The low number of data points (n=2) guarantees that the Parker relationship (for > 2 mm particles) and the power function (for < 2 mm particles) would reasonably fit the data. Therefore, the following extrapolation of these relationships to higher discharges based on only these two points should be considered very preliminary, and is presented primarily to show the direction that we are taking with this sampling. The Parker 1979 bedload transport curve was best fit to the measured data with a τ_{ref} value of 1.20 lbs/ft^2 (Figure 32). The WY 1998-2000 annual hydrographs are illustrated in Figure 33, and daily

Figure 31. Plot of shear stress as a function of discharge at the Igo Gaging Station

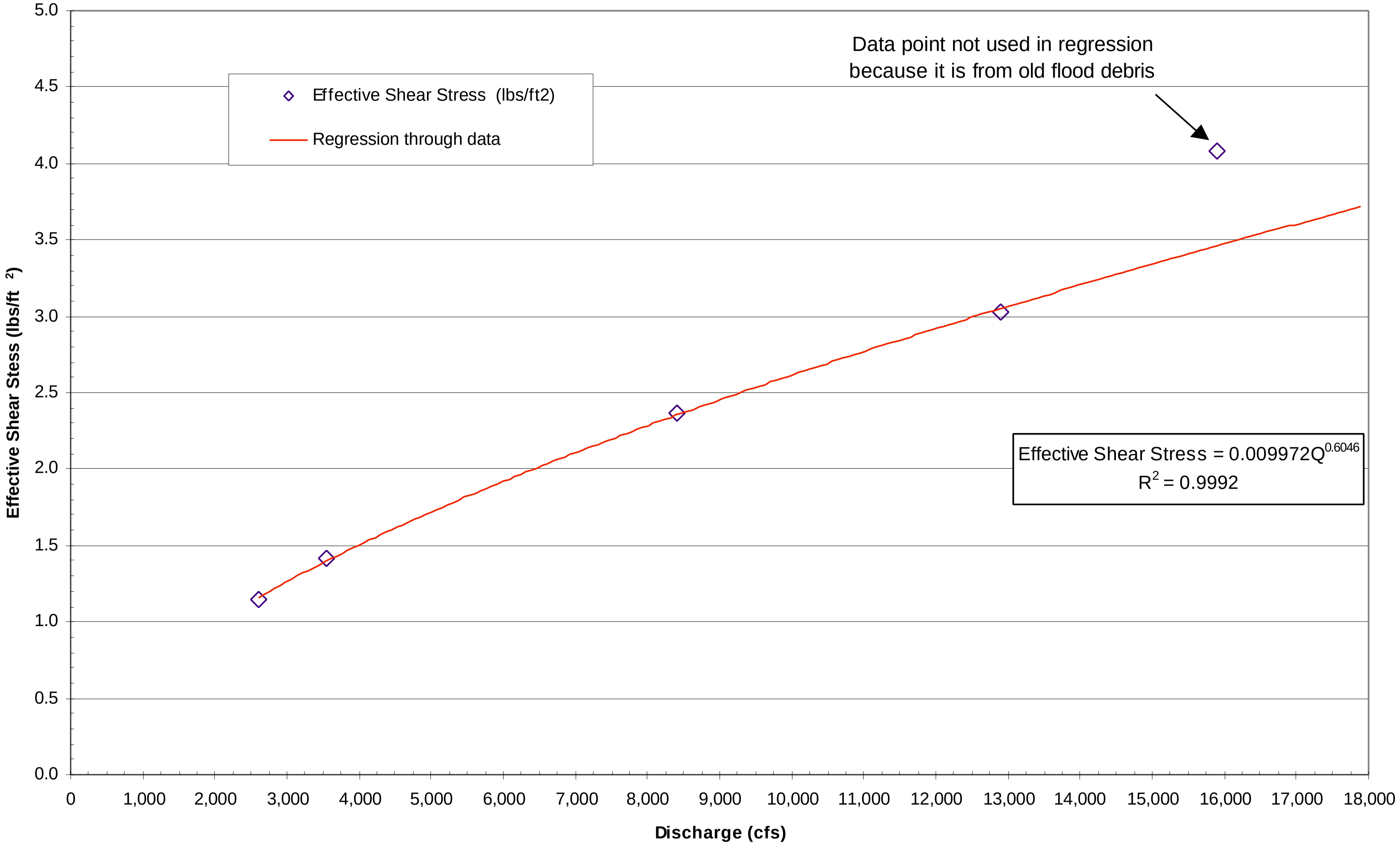


Figure 32. Plot of bedload transport data with Parker 1979 bedload transport fitting function for particles > 2 mm and a power function fit for particles < 2mm

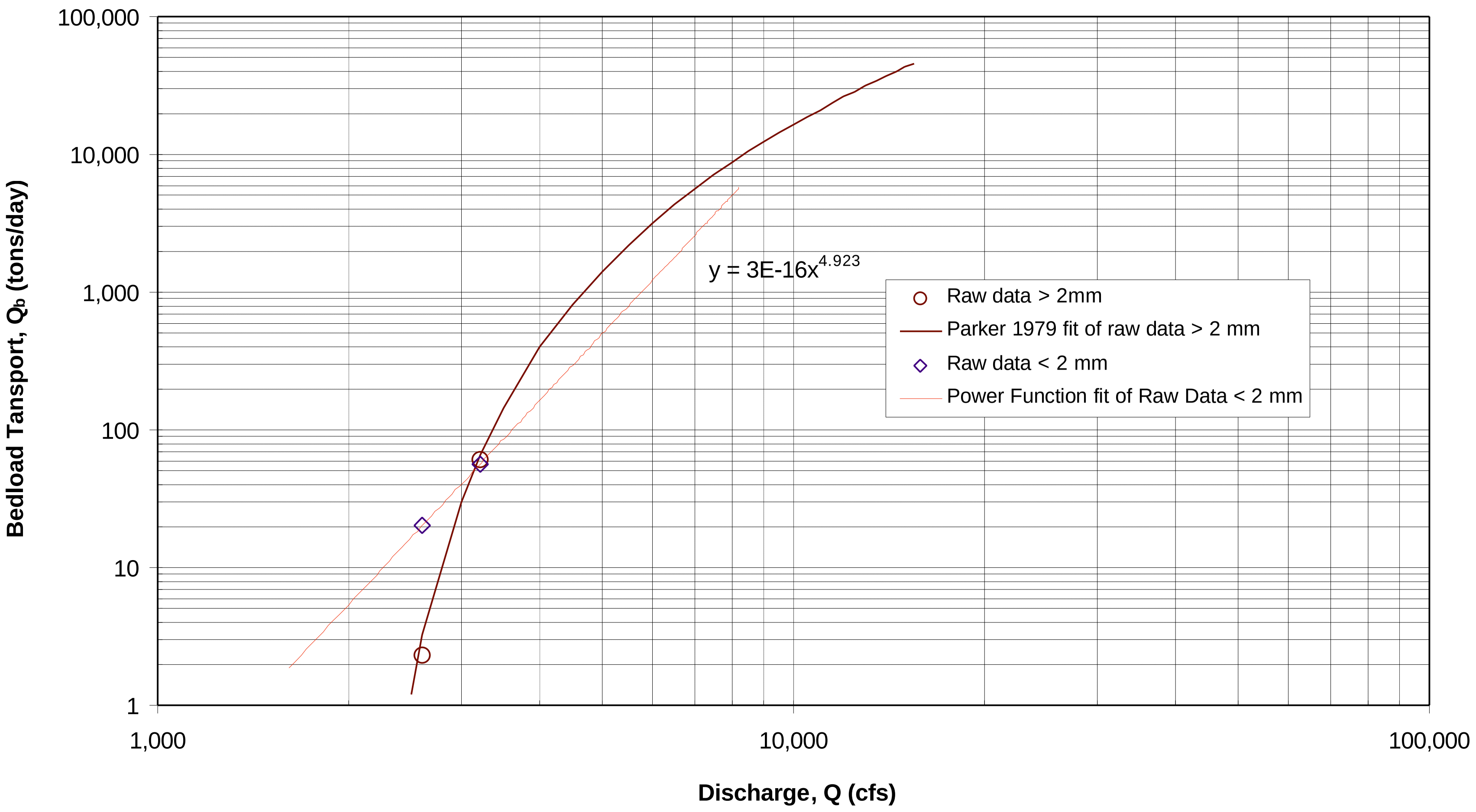
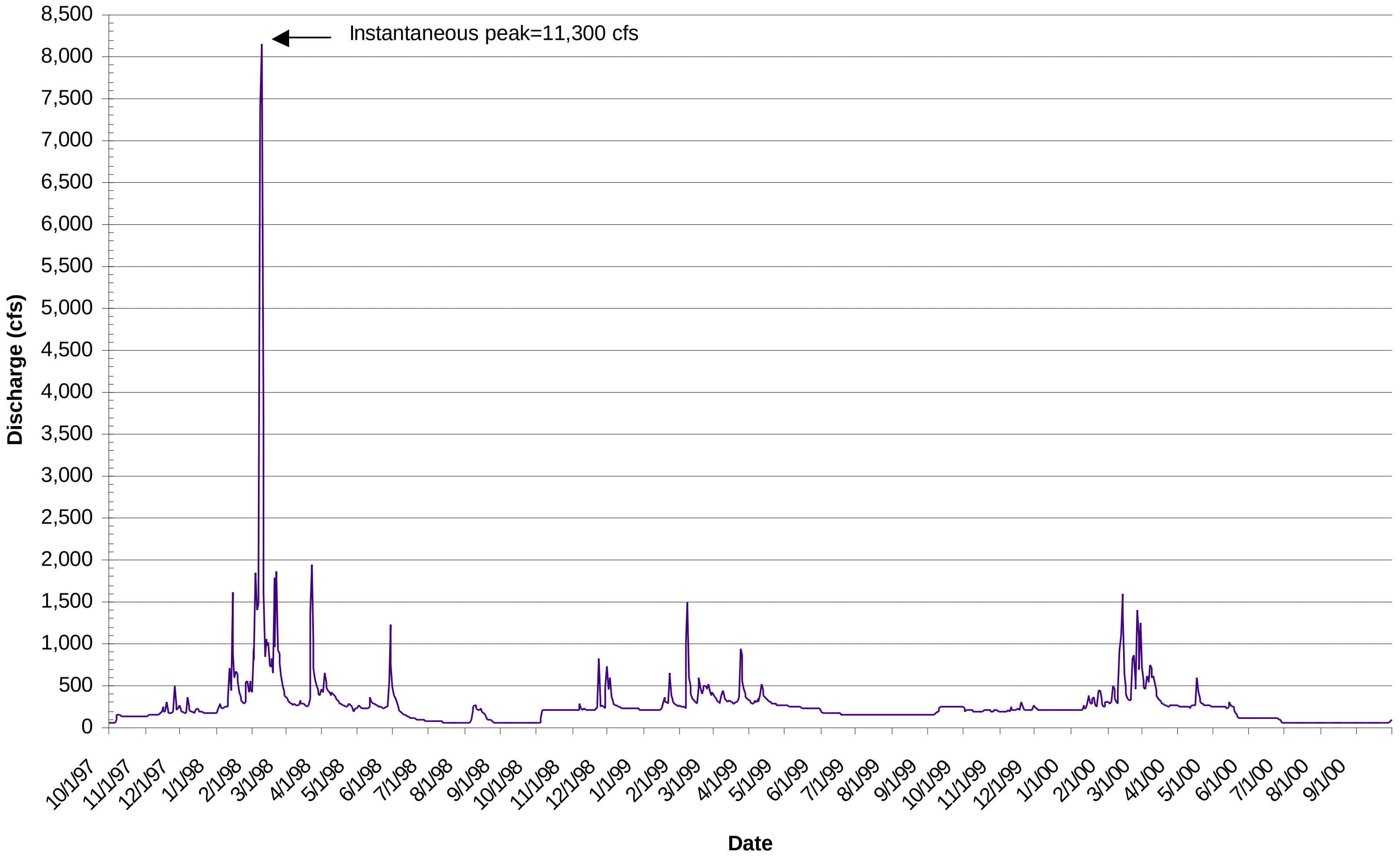


Figure 33. WY 1998-2000 hydrograph at the Clear Creek near Igo gaging station.



Instantaneous peak=11,300 cfs

bedload transport results for coarse bedload and fine bedload are tabulated in Appendix B. Bedload transport flux was computed by applying 1-hour streamflow data to the bedload transport curve (Figure 32). Overall bedload transport during WY 1998-2000 is summarized in Table 10. Because the coarse bedload data was fitted to a bedload transport curve rather than a power fit curve, the uncertainty of extrapolation to higher discharges should be less than the fine bedload transport curve. However, with only two data points, both predictions should be considered extremely preliminary.

Table 10. Summary of annual bedload transport estimates for WY 1998 – 2000 at Igo Gaging Station

Water year	Instantaneous peak discharge (cfs)	Coarse bedload transport (tons)	Fine bedload transport (tons)
1998	11,300	18,900	15,300
1999	2,710	2.4	12.8
2000	2,520	0	8.0

5.4.3. Discussion

This section discusses how this sampling effort satisfied the objectives in Section 5.4, with discussion focusing on:

- flow threshold for coarse sediment mobility, and relate to flood frequency
- bedload transport data curve fitting
- sampling location

5.4.3.1. Coarse bedload transport threshold, and relation to flood frequency

Our data suggest that mobility of gravel and cobble-sized particles does not occur at discharges below 3,200 cfs. However, evidence of pea-gravel sized particles in our 3,200 cfs bedload sample suggests that 3,200 cfs is not far from the mobilization threshold for larger particles. In the absence of additional bedload data and the results of the bed mobility modeling on the cross section, our professional judgement is that gravels and cobbles in the canyon reach probably begin to be mobilized by flows greater than 4,000 cfs, as do cobble riffles and point bars in downstream alluvial reaches. Marked rock experiments at a typical alluvial riffle (XS 411+66) at Reading Bar, which is the first alluvial reach below the Clear Creek canyon, suggest that large gravels and cobbles (D_{84}) were only partially mobilized by a 2,700 cfs flow (Table 5), which also tends to corroborate results of our bedload measurements.

Even though the 3,200 cfs discharge is not considered large enough to exceed the coarse sediment mobility threshold, comparing the post-Whiskeytown Dam flood frequency of this flow to the pre-dam flood frequency is useful to illustrate the impact of the dam on sediment transport thresholds. This discharge (3,200 cfs) is less than a 1.09-year flood frequency using pre-dam flow data, while it is a 2.0-year flood frequency using post-dam flow data. The current conceptual model for bed mobilization on healthy alluvial rivers (based on bed mobility threshold observations by ourselves and other researchers) suggests that bed mobilization begins at discharges slightly smaller than the 1.5 to 2.0 year flood magnitude. This model suggests that if this sampling would have occurred prior to the dam, the coarse sediment transport threshold shouldn't have been exceeded because 3,200 cfs is substantially less that the pre-dam 1.5-year flood (5,770 cfs). However, if we do the same exercise using the post-dam data ($Q_{1.5}$=2,060), we should have expected the coarse sediment transport threshold to have been exceeded because 3,200 cfs is larger than the post-dam 1.5-year flood.

So, why wasn't the threshold exceeded by 3,200 cfs? Often, large storage reservoirs reduce flood flows and coarse sediment supply, causing the channelbed to coarsen and rarely mobilize to the point where it may require a 5 to 10 year post-dam flood to mobilize the bed. The channelbed typically responds to the reduced coarse sediment supply by winnowing (smaller gravels are selectively transported out of the reach, leaving the coarser particles behind) and coarsening (Dietrich, 1987). Lastly, the loss of upstream coarse sediment supply reduces the ability of the river downstream of the dam to adjust its dimensions and scale itself down to the new and smaller flow regime. The result is often a channel geometry that is the same size as the pre-dam channel, the particle size is coarser than the pre-dam bed surface, and in combination with a large channel reflecting the pre-dam flow regime (compared to the new smaller flow regime), coarse sediment transport is discouraged.

The solution to this problem is two-fold: increase flood flow magnitude and frequency, and greatly increase coarse sediment supply to restore instream sediment storage and offset bed coarsening trends that have occurred since 1963 when the dam was completed. Increasing the frequency of flow events in the 4,000 cfs to 6,000 cfs range should be a future restoration goal to restore a more natural frequency of bedload transport events. Smaller flows (2,000 cfs to 3,000 cfs) naturally occur occasionally from tributary flows below Whiskeytown Dam, and larger floods (>10,000 cfs) still occur during large storm events, but Whiskeytown Dam has greatly reduced the moderate floods in the 4,000 cfs to 6,000 cfs range. In addition, spawning habitat has been reduced by 93 percent (an indicator of decreased coarse sediment storage and increased fine sediment storage) downstream of Whiskeytown Dam between 1963 and 1970 (Coots, 1971). Gravel introduction efforts by the Clear Creek Restoration Program immediately downstream of Whiskeytown Dam are an important first step to restoring this lost coarse sediment supply, and should be increased in the future. This increased supply will reduce the size of substrate in the channel and lower the discharge threshold for coarse sediment transport.

5.4.3.2. Bedload transport curve fitting

The small sample size of bedload transport measurements obviously decreases our ability to accurately predict bedload transport rates over the full range of discharges expected on Clear Creek. In addition, the close proximity of the South Fork of Clear Creek may cause sediment transport measured at the Igo gaging station to be largely a function of sediment pulses originating from South Fork Clear Creek rather than the mainstem of Clear Creek itself. This may cause large fluctuations in sediment transport rating curves as episodic sediment pulses are delivered to the gaging location from South Fork Clear Creek. If additional sediment transport samples are collected at this location and added to existing data, the source of the high flow event should be noted (tributary generated or a spill event from Whiskeytown Dam) to evaluate whether sediment transport is consistent between the two sources of high flows. Additional data will also help evaluate whether the Parker 1979 curve does a reasonable job fitting the data, or whether a different curve fit equation should be considered.

5.4.3.3. Bedload sampling location

The confined location and moderate gradient at the USGS sampling site caused dangerous sampling conditions for flows greater than approximately 5,000 cfs. In addition, the potential fluctuations in sediment transport rating curves due to episodic sediment pulses from the South Fork of Clear Creek may cause rating curves to be extremely variable. After much consideration of objectives and data uses, we recommend moving the sediment monitoring site to the Renshaw Riffle cross section 273+65. This location is much lower gradient, is safer to sample, and is at the entrance to the low-gradient alluvial reach that extends to the Sacramento River confluence. Also, because there are no significant tributaries immediately upstream to episodically deliver coarse sediment, bedload transport rating curves should be more stable. This site would also quantify sediment input into the Lower Clear Creek Floodway Rehabilitation Project.

5.5. **Bedload Transport Modeling**

Bedload transport modeling predicts the rate of bedload transport as a function of discharge based on channel geometry, bed surface particle size, and hydraulic conditions as a function of flow (shear stress).

The best estimates of bedload transport are derived from time-integrated volume change in a sediment trap (e.g., measuring how much bedload is deposited in a sedimentation basin with 100% trap efficiency over a storm hydrograph). This technique samples over the entire hydrograph (long sampling time), and almost always requires an artificially constructed sediment trap. Bedload transport measurements, as reported in the previous section, are the next best method to estimate bedload transport rates. However, this approach is limited by short sampling time (often 60 seconds per vertical) and samples are usually collected at a small number of points on the storm hydrograph. While field based estimates of bedload transport are usually preferable (more accurate) to modeling approaches, they require considerable amounts of field time and high flows in order to gather the data. Additionally, these methods document bedload transport under existing conditions only, and do not allow gaming of different channel geometry and sediment supply conditions.

Bedload transport modeling provides the practitioner the ability to predict bedload transport rates without the need for empirical bedload transport measurements, and allows gaming of different flow, sediment supply, and channel geometry alternatives. The primary drawback to bedload transport modeling is that the predictions are imprecise, and usually inaccurate compared to the bedload transport rate that would actually be occurring (Gomez and Church, 1989). We applied bedload models at three sites for different purposes. First, modeling was performed at the Peltier Valley Bridge bedload transport modeling study site (RM 16.5) to compare and contrast theoretical coarse sediment transport rates under existing sediment starved conditions with that if a large spawning gravel transfusion occurred. Second, we modeled bedload transport at the Igo gaging station site to compare our two bedload transport measurements to modeled predictions. Lastly, we modeled bedload transport rates at the Floodway Rehabilitation Project Site to evaluate the effect of two differing design slopes in the project reach on theoretical coarse sediment transport rates. For the Floodway Rehabilitation Project Site, we had originally planned on applying a HEC-6 sediment routing model to the reach, and we subsequently felt that applying the surface-based Parker transport equation using reachwide hydraulics for each of the two slope conditions would be a better approach to evaluate the differences in coarse sediment transport rates.

5.5.1. *Methods*

The reach-scale gravel transport model adapts the surface-based bedload equation of Parker (1990 a,b) to calculate gravel transport rate and Shields stress at different discharges in natural rivers. The input parameters to this reach-scale gravel transport model include channel cross section, channel surface grain size distribution, water discharge, floodplain Manning's *n*, and reach-average water surface slope. The specifications of those parameters are listed in Table 11.

Table 11. Input parameters to the Parker surface-based reach scale gravel transport model

	Input parameters	**Note**
1	Channel cross section	Must identify edges of the main channel, which is often marked with abrupt slope change and dense vegetation. The main channel coincides with bankfull channel in most cases.
2	Grain size distribution of the channel surface	Can use pebble count data; must exclude particles finer than 2 mm.
3	Water discharge	Can be a single discharge, range of discharges, or a flow duration curve. If a duration curve is used, the output will be average bedload transport rate in addition to bedload transport rate as a function of water discharge.
4	Floodplain Manning's n	Can assign different Manning's n values for left and right floodplains.

5	Reach average water surface slope	Water surface slope is an approximation of friction slope. It can be further approximated with average bed slope if the reach is long enough.

Model output includes bedload transport rate for particles greater than 2 mm, bedload grain size distribution and normalized Shields stress. If a flow duration curve is used as input parameter in place of a single discharge, the output will be average bedload transport rate and grain size distribution associated with the flow duration curve. In addition, the model will also provides bedload transport rate and normalized Shields stress as functions of different discharges.

Although the surface-based bedload equation of Parker (1990a,b) is widely regarded as the best bedload transport equation available, it still has limitations. As stated by Parker (1990b): "*the calculation of bedload transport* (with the surface-based bedload equation) *in gravel rivers yields at best crude approximations of the actual observed numbers in field streams*." Based on experience with Parker equation (1990a,b) and other sediment transport equations, we estimate that the reach-scale model yields bedload transport estimates that are accurate within an order of magnitude. We believe that most of the results are accurate within a factor of 2 to 3, and in rare cases, a factor of more than 5. The calculated bedload transport rate represents the maximum bedload transport rate (i.e., transport capacity) in the channel with the given discharge or duration curve and unlimited sediment supply. The calculated bedload grain size distribution represents the momentary value in case of a single discharge, or the integrated value over a period of time if a duration curve is used.

5.5.1.1. Peltier Valley Bridge Study Site

For the Peltier Valley Bridge bedload modeling site (Figure 20A and Figure 21), six cross sections were surveyed to represent reach topography (Appendix C), and "average" cross section geometry developed for the reach. The low flow water surface slope (200 cfs) and 1997 flood debris slope (appx 15,000 cfs) was surveyed through the reach, and the regression line through the 1997 flood profile (slope = 0.0036) was used to estimate high flow water surface slope for the bedload transport model (Figure 34). A surface pebble count was collected around cross section 891+80 to represent existing reach-wide particle size distribution (D_{84}=255 mm, D_{50}=124 mm) (Figure 35). The purpose of this exercise was to assess some of the bedload transport rate tradeoffs of a large-scale gravel transfusion on the reach. This transfusion would greatly decrease the reach average particle size and change channel geometry, thereby increasing bedload transport rates to some unknown degree. To represent potential future gravel bed particle size conditions, we developed a more desirable particle size distribution for spring-run chinook salmon spawning based on well sorted, clean spawning gravel deposits sampled near cross section 883+25 (Figure 35). The bedload transport model was then run for the same hydraulic conditions, but for different bed particle size distribution to compare the difference in transport rates between existing conditions and potential future conditions. Channel geometry and hydraulics were assumed to be the same for both conditions, with particle size being the only variable adjusted for this gaming exercise. The model was run to predict transport rates for particles greater than 2 mm.

5.5.1.2. Igo Gaging Station

At the Igo Gaging station site (Figure 24), only cross section 571+10 at the USGS cableway was used to characterize channel geometry in this modeling effort (Figure 29). We measured high flow water surface slopes at a variety of discharges, and found the slopes to vary as a function of discharge (Figure 30). To incorporate this variability, we ran the bedload transport model at several different slopes to evaluate the sensitivity of model predictions to slope (ranging from 0.00378 to 0.00497). The slope when the 1998 bedload samples were collected was 0.00378, so the predicted transport curve using this lower slope

Figure 34. Peltier Valley Bridge bedload modeling site longitudinal profile survey

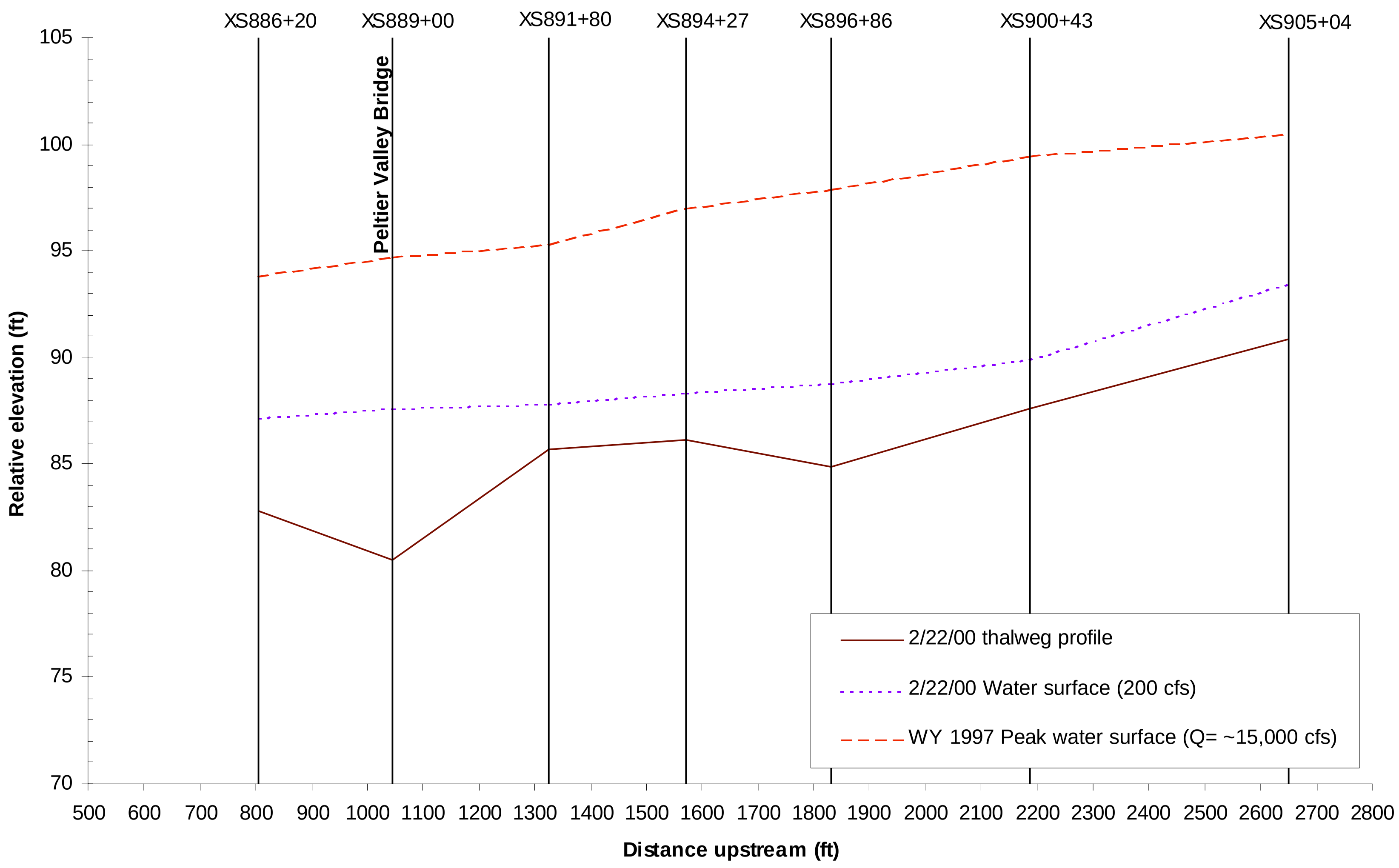
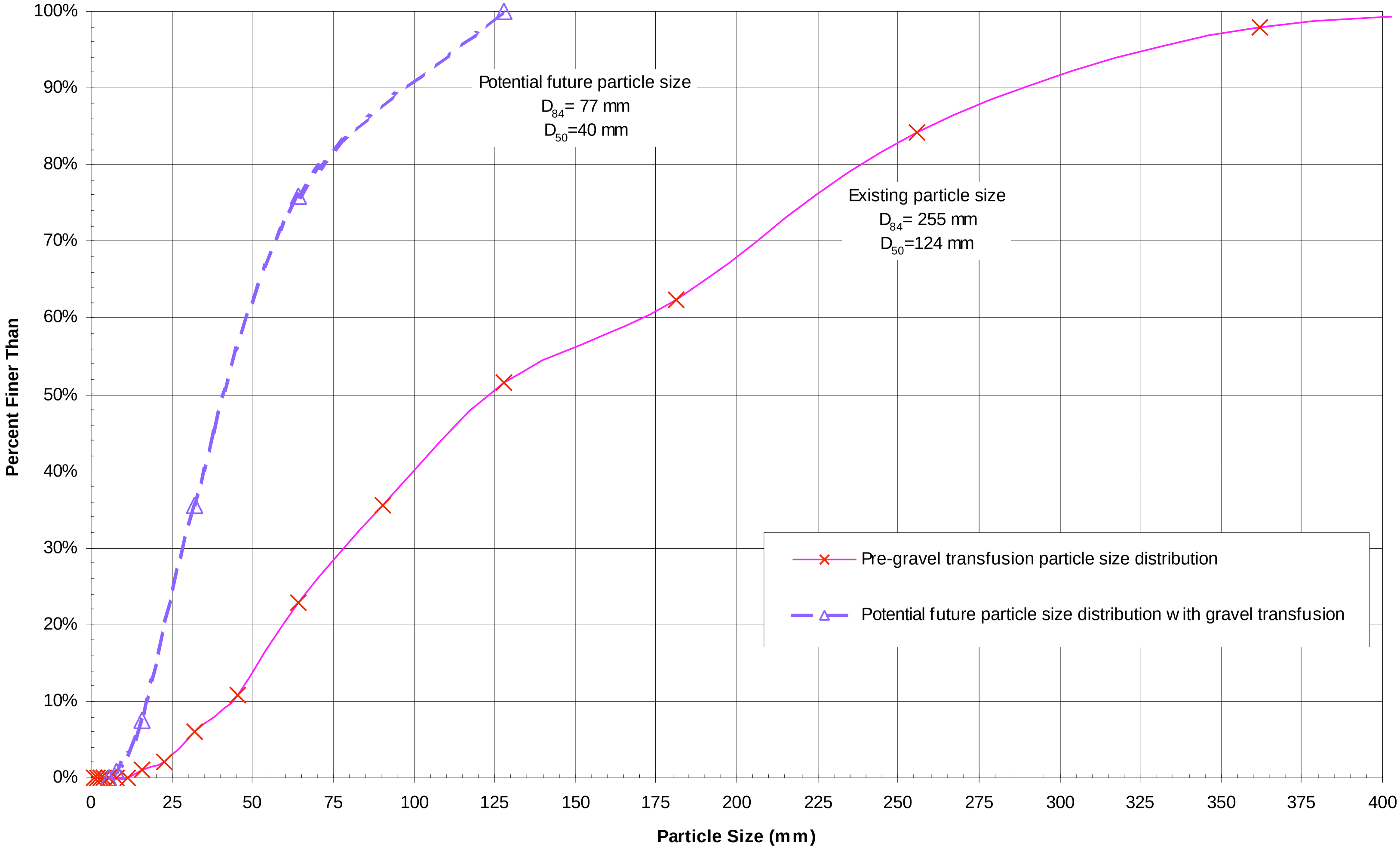


Figure 35. Existing and potential future particle size distribution with gravel transfusion at the Peltier Valley Bridge bedload modeling study site



should be used when comparing predicted versus measured transport rates below 4,000 cfs or so. A pebble count was collected around cross section 571+10 to characterize existing particle size distribution (Figure 36), but because we did not attempt to model future transport conditions here (as was done at the Peltier Valley Bridge site), we did not develop a "future" bed particle size distribution at this site. The modeling at this site was done for the ESSA decision making project, which used transport of particles > 8 mm rather than the 2 mm used at the Peltier Valley Bridge site and Floodway Rehabilitation Reach. Because the purpose of this site is to compare predicted results versus modeling results, using 8 mm instead of 2 mm will not impair our ability to make this comparison.

5.5.1.3. Floodway Rehabilitation Reach

At the Floodway Rehabilitation Reach, the design incorporates two reaches that have a lower slope (0.0015) than the majority of the reach (0.0023), and there was concern whether this difference in slope would result in local deposition and channel instability. Therefore, we applied the bedload transport model to compare the difference in predicted bedload transport between the reaches. Five cross sections of virtually identical channel geometry were chosen to represent sub-reach conditions at the rehabilitation site (Figure 37 and 38), and the local slopes were used to model each cross section individually (Table 12). Future particle size distribution was developed from cleaned borrow material from the Shooting Gallery borrow site, and this distribution was applied to all five cross sections (Figure 39). The model was run to predict transport rates for particles greater than 2 mm.

Table 12. Summary of cross sections and slopes used for the Floodway Rehabilitation Project site bedload modeling.

Cross Section	Slope
204+10	0.0023
186+50	0.0015
166+80	0.0023
137+96	0.0015
128+20	0.0023

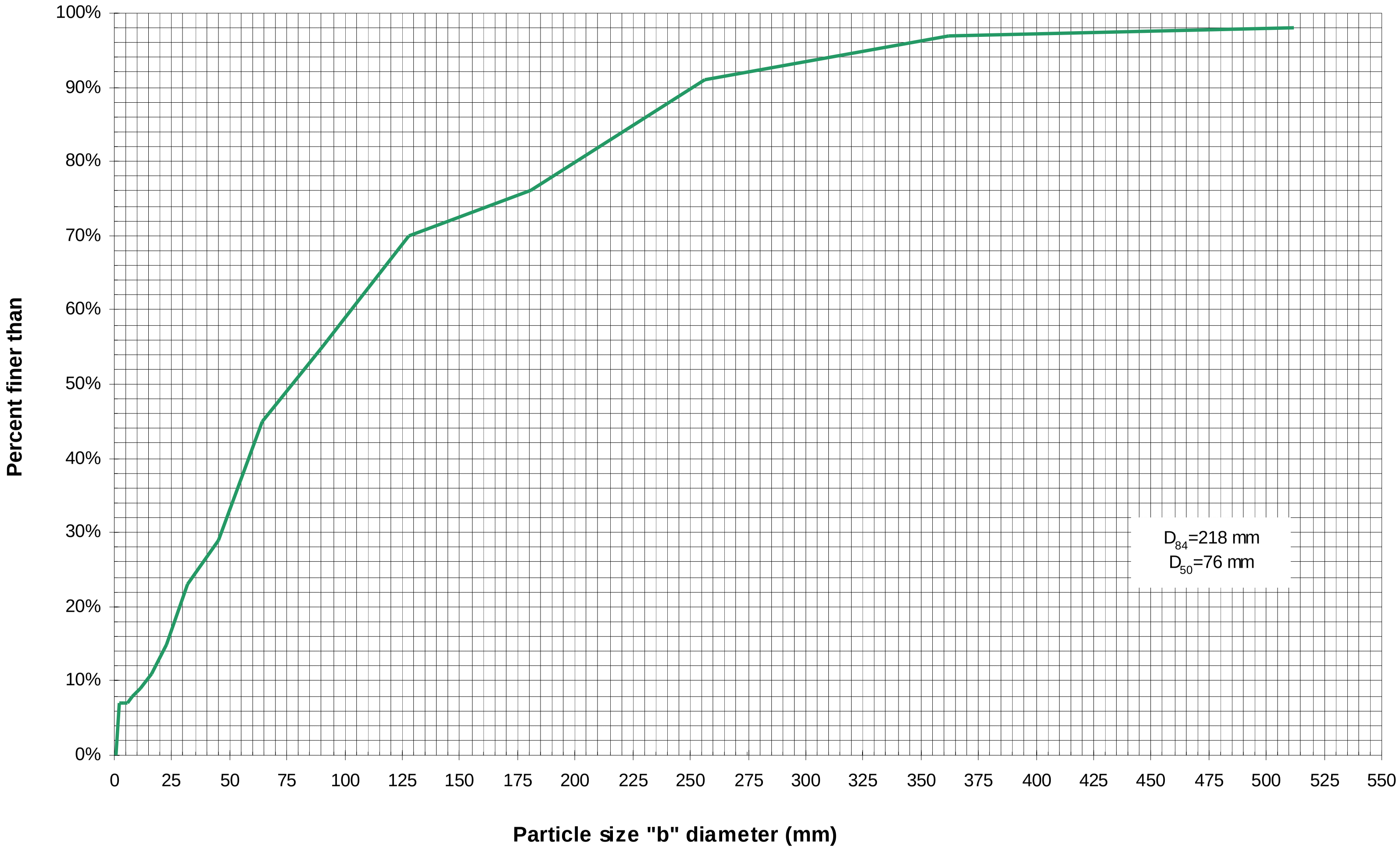
5.5.2. Results

The numerical results of the bedload modeling exercise should be tempered by Parker's acknowledgement that they are "*crude approximations at best of the actual observed numbers in field stream*", and that the best use of the modeling exercise should be to evaluate trends rather than apply the absolute numerical predictions.

5.5.2.1. Peltier Valley Bridge Study Site

As expected, predicted bedload transport rates are very small under existing, sediment starved, and highly paved channelbed conditions (Figure 40). Significant bedload transport does not begin to occur until streamflows exceed 5,500 cfs, which is corroborated with our field observations of a very coarse and armored bed surface (with angular particles). By simulating potential improved coarse sediment supply conditions by "converting" the bed particle size distribution to one more favorable to salmonid spawning, we greatly increase predicted bedload transport rates, sometimes over 3 orders of magnitude increase. We also theoretically lower the discharge at which significant bedload transport occurs down to 1,000 cfs. Several important caveats need to be reiterated with this analysis. First, even with large gravel introduction efforts, the bed surface would not be universally finer (as implied in our "post-transfusion" modeling assumption), such that actual predicted bedload transport rates would be lower than that predicted by the "post-transfusion" curve in Figure 40. In other words, the predicted "post-transfusion" curve would likely move to the right under actual field conditions, but the actual location of the curve would be highly uncertain. Second, the modeling approach assumed the same slope for all ranges of

Figure 36. Bed surface particle size distribution at cross section 571+10 at the USGS cableway just upstream of the old Placer Road Bridge



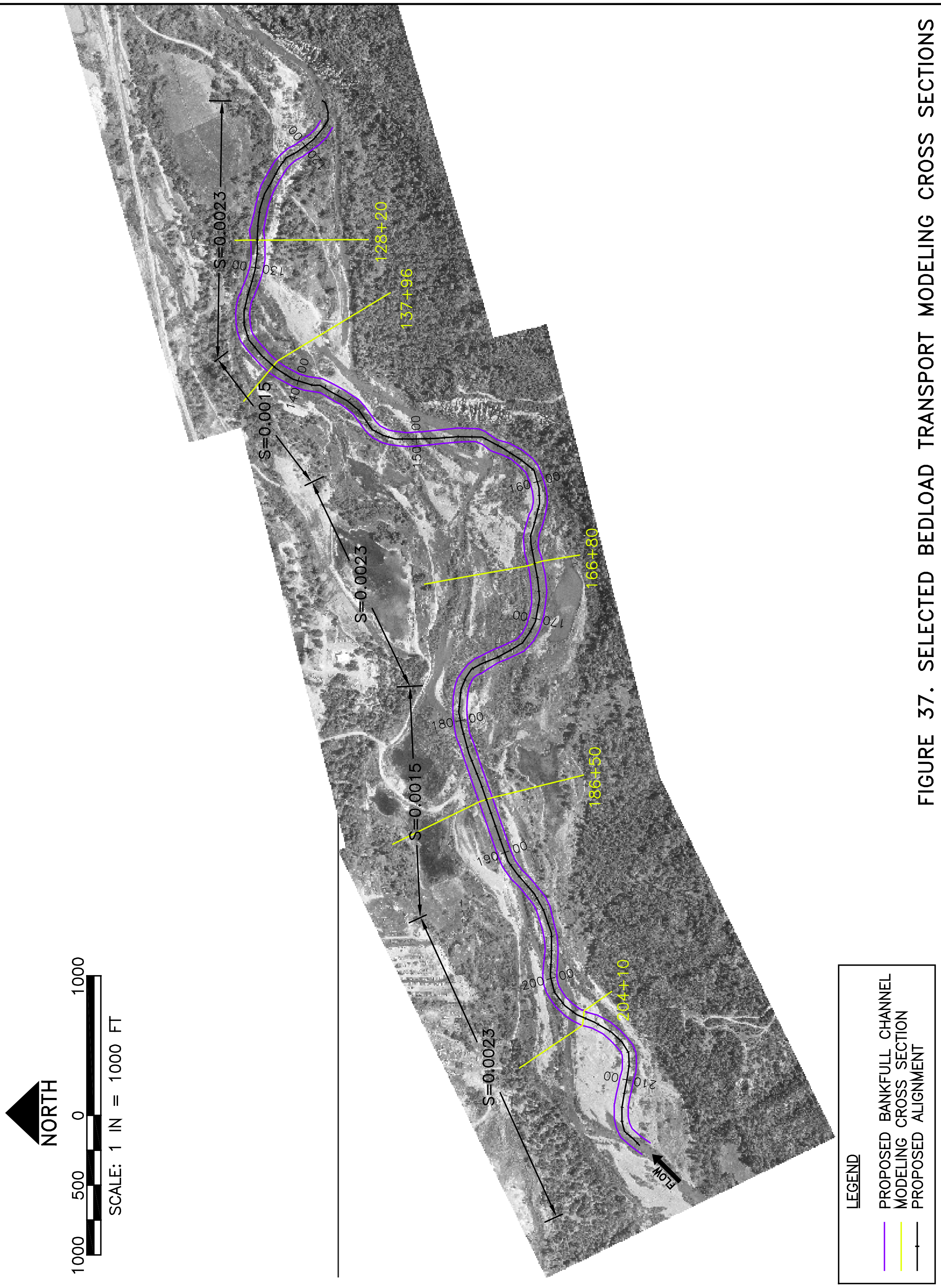
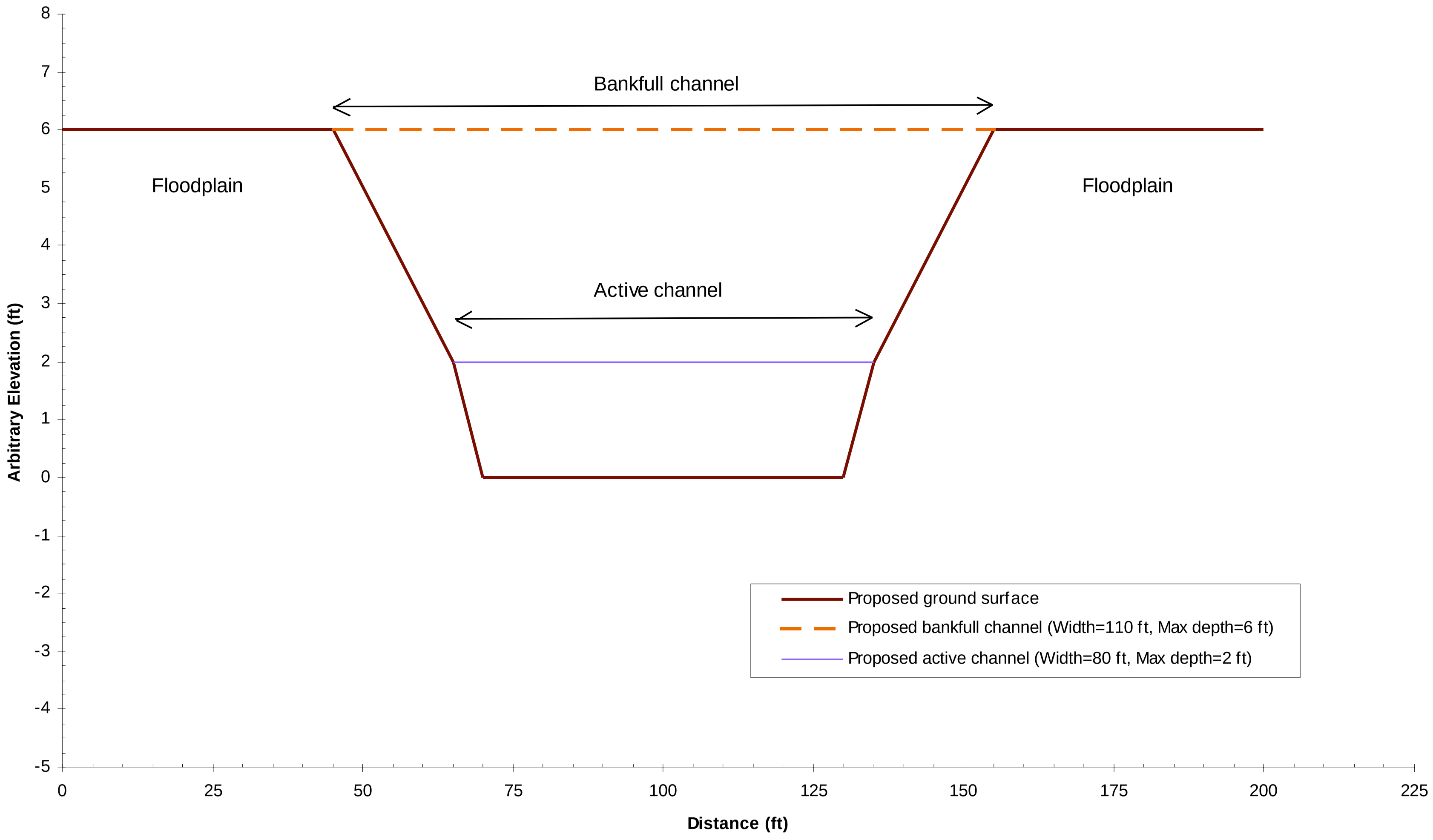


FIGURE 37. SELECTED BEDLOAD TRANSPORT MODELING CROSS SECTIONS AT THE FLOODWAY REHABILITATION PROJECT SITE

12/19/01

Figure 38. Riffle cross section template for the Clear Creek Floodway Rehabilitation Project



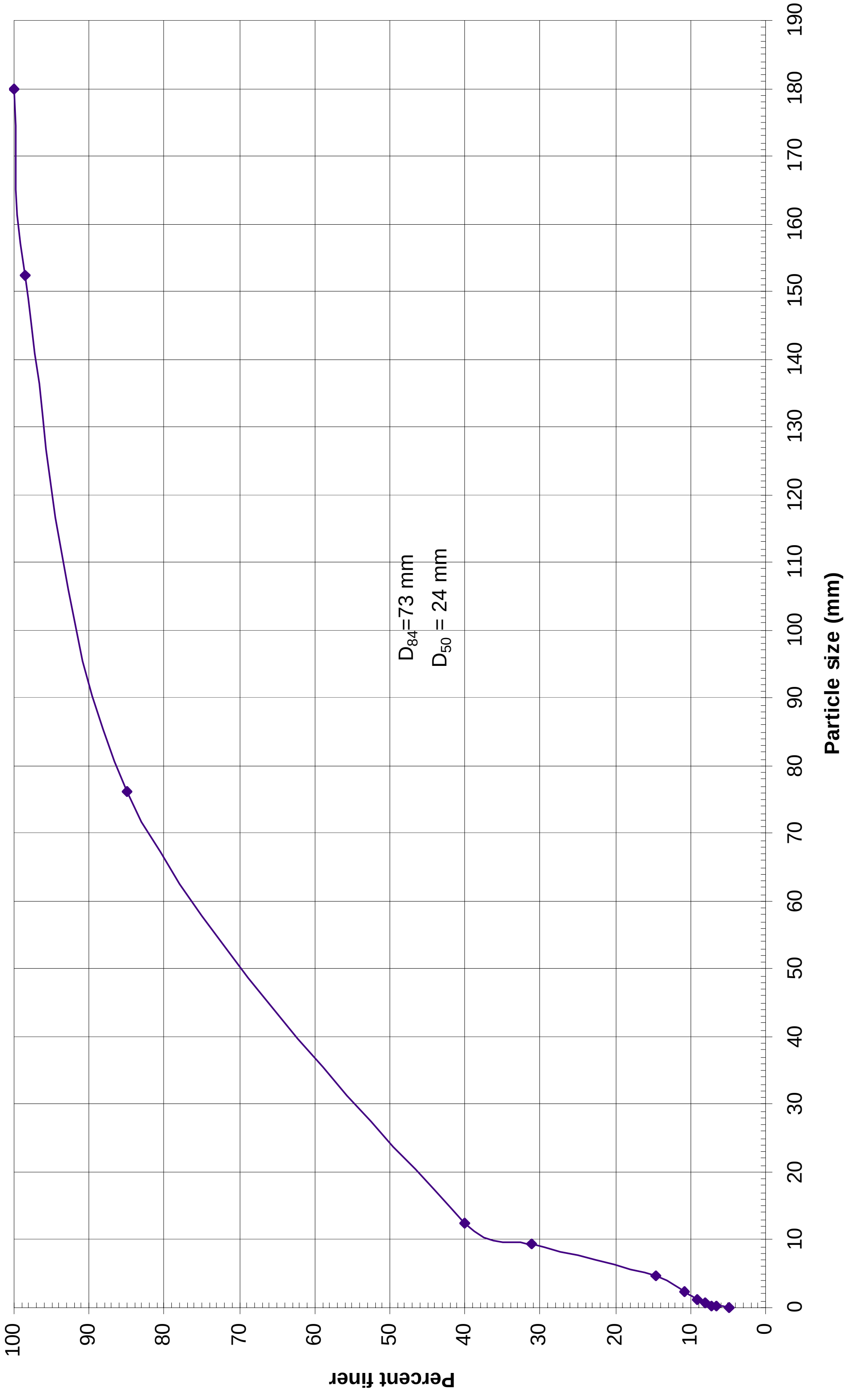
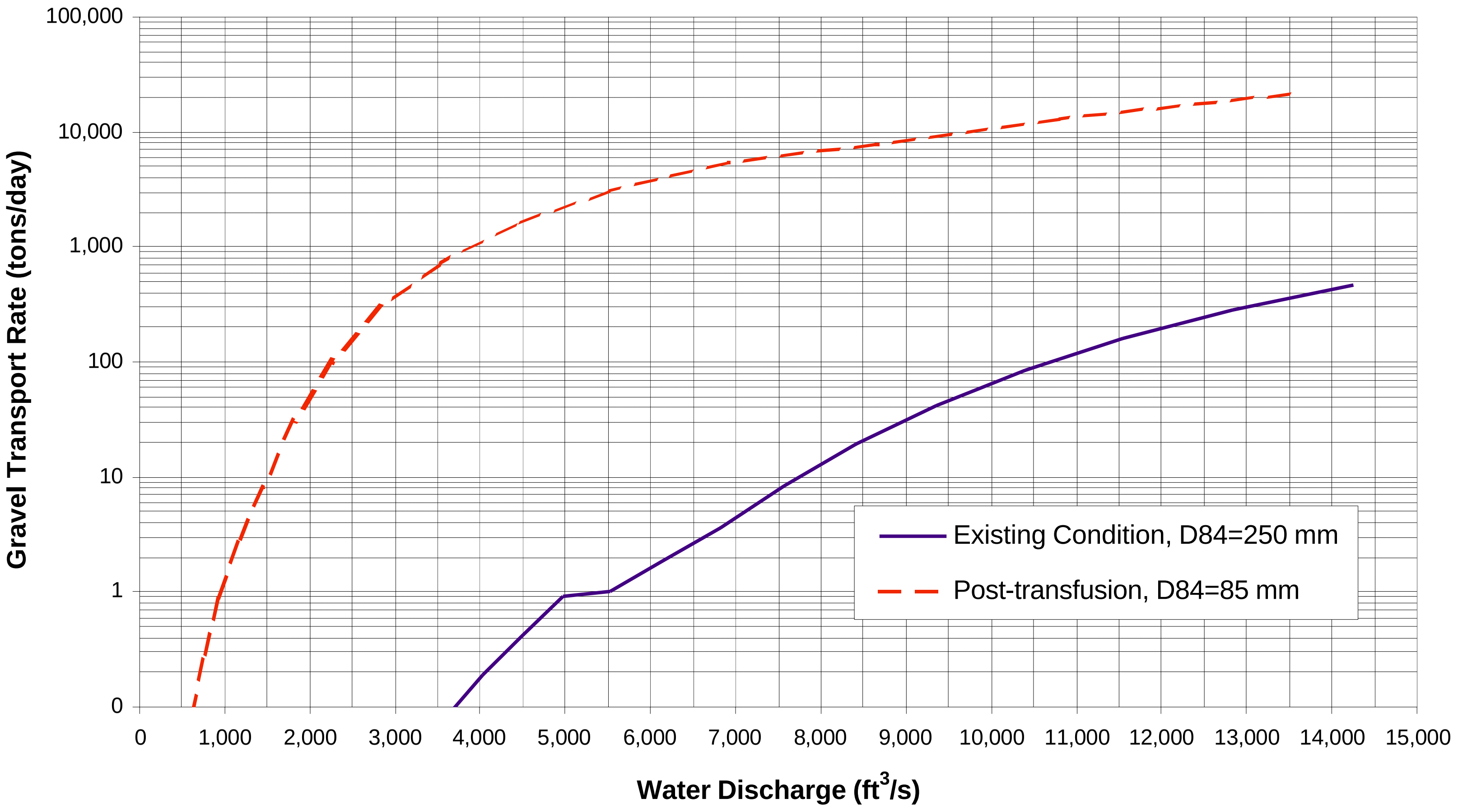


Figure 39. Proposed particle size distribution for the Floodway Rehabilitation Project

Figure 40. Peltier Valley Bridge bedload modeling site transport relationships (> 2 mm) under existing conditions (armored) and under simulated future conditions with large scale gravel introduction reducing bed surface particle size distribution



discharges, and as shown at the Igo Gaging Site in Figure 31, slope does change with discharge at most sites. Because we were not able to measure water surface slope at a wide range of discharges (as was done at the Igo Gaging Station site), our assumption of slope from the 1997 flood likely overpredicted slope at lower flows, which will also result in a shift to the right in the curve in Figure 40.

Perhaps the best use of this analysis is to illustrate the tradeoffs between gravel introduction, flow magnitude, and flow duration rather than focus on the absolute numerical predictions. The first point is: *The more gravel you add, the greater the potential bedload transport rate, thus the more gravel you need to add to maintain storage*. This apparent increasing cycle would eventually end once the bed surface was converted to the particle size of the gravels being introduced; however, this complete conversion in particle size is probably not desirable because large volumes of gravel would be required to do this, and a mix of substrates from finer gravels to boulders provides greater aquatic habitat diversity than that provided by a total conversion of the bed surface to the less diverse introduced gravels. The second point is: *As the channel morphology and particle size is scaled down through channel rehabilitation and gravel introduction efforts, the flow magnitude to surpass geomorphic thresholds should decrease from present conditions*. The clearest example of this point is that it takes a much smaller flow magnitude to mobilize a 100 mm particle than a 250 mm particle. The third point is: *high magnitude and short duration flows are much more water-efficient at mobilizing, scouring, and transporting coarse sediment than moderate magnitude and long duration flows due to the steepness of the transport curve*. To illustrate this example, we'll use the "post-transfusion" curve in Figure 40, with appropriate caveats described in the previous paragraph. Let's assume that we want to transport 1,000 tons of gravel with a high flow release. We could release 2,200 cfs for 10 days to transport the 1,000 tons (requiring 43,600 acre-ft of water), or we could take a more efficient approach and release 4,000 cfs for one day (requiring 7,900 acre-ft of water). In this example, the short-duration high flow saves over 35,000 acre-ft of water, requiring only 18% of the water needed for the long-duration moderate flow release. Additionally, the higher the release, the more geomorphic thresholds are achieved (e.g., bed scour and redeposition, channel migration).

5.5.2.2. Igo Gaging Station

As stated above, the primary use of the bedload modeling exercise at the Igo Gaging Station site is to compare bedload modeling predictions to the two samples measured during high flows in 1998. Recall that this analysis predicts bedload transport for particles greater than 8 mm, and uses existing conditions for bed particle size disribution. The bedload transport developed by the model in Figure 41 reflects predicted transport rates of a variety of slopes based on those shown in Figure 30 and 31. When comparing measured transport rates with model predictions, we should use the lower most transport curve (slope=0.00378) because it was developed by using a slope comparable to that when the samples were collected (slope=0.00332 to 0.00378). This suggests that the lower-most curve is a reasonable predictor of bedload transport, only deviating by a factor of 2 to 3 from the 3,200 cfs measurement. Comparison between modeling results and actual measurements commonly deviate by an order of magnitude or more. The other predicted bedload transport curves may be more appropriate for flows greater than 5,000 cfs where slope increases.

5.5.2.3. Floodway Rehabilitation Reach

Bedload transport modeling at the Floodway Rehabilitation Reach suggests an order of magnitude difference of coarse sediment transport at 3,000 cfs between the two slopes (Figure 42). Recall that the proposed channel geometry dimensions and particle size are virtually identical through the entire reach, such that the lower slope in two subreaches (S=0.0015) is the primary differing variable. The difference in bedload transport rate caused by this lower slope suggests that an adjustment in channel geometry should be considered to prevent these lower slope reaches from aggrading during a high flow event. The proposed design channel width is 110 ft and channel depth is approximately 6 ft for all reaches. Based on the results of the bedload transport model, we recommend that the channel dimensions be reconsidered in

Figure 41. Igo Gaging Station bedload modeling site transport rating curves for bedload (> 8 mm) and comparison to 1998 bedload transport rate measurements

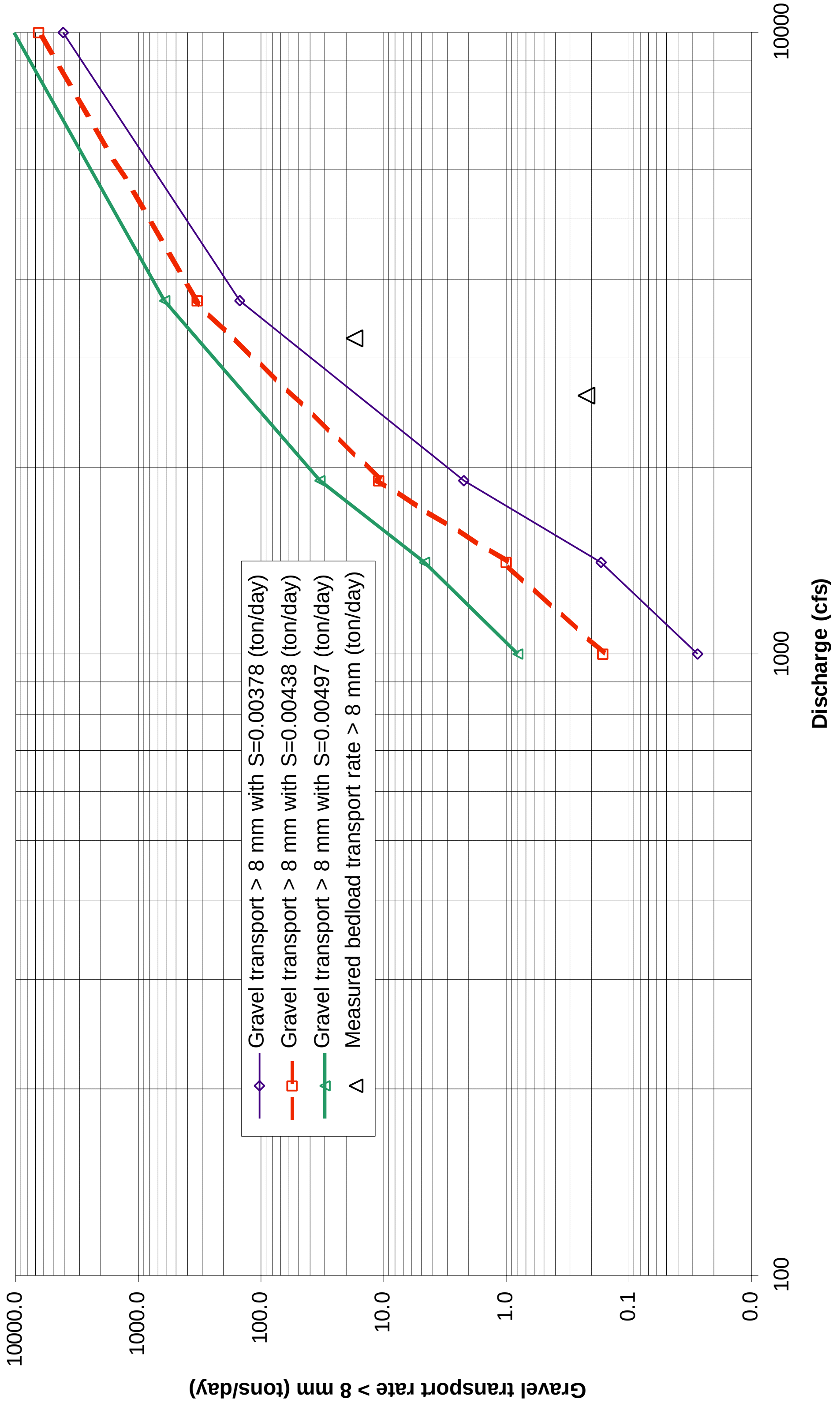
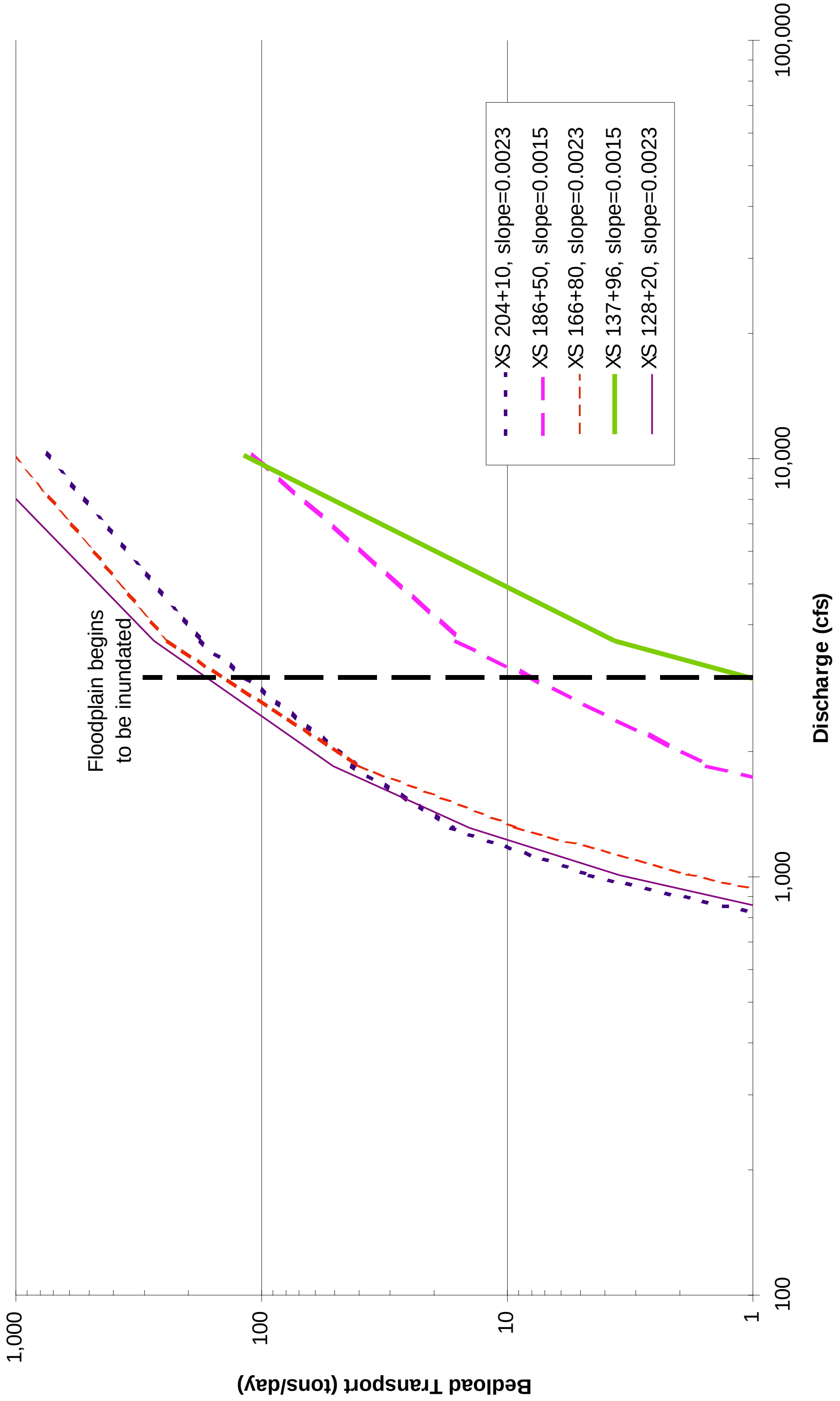


Figure 42. Comparison of bedload transport rating curves for five cross sections in Floodway Restoration Project, illustrating the potential effect of lower gradient (S=0.0015) subreaches within steeper gradient (S=0.0023) project reach.



these two lower gradient reaches (Figure 37), specifically reducing width moderately and increasing depth slightly to increase bedload transport capacity in the lower gradient reaches closer to the transport capacity in the steeper gradient reaches. The bedload transport model should then be run again with this new channel geometry in the lower gradient reaches to evaluate whether bedload transport rates have been increased to those in the higher gradient reaches.

6. RESTORATION AND MANAGEMENT RECOMMENDATIONS

The historical geomorphic and hydrologic context for Lower Clear Creek provided in earlier sections of this report describes cumulative changes to the function and form of the stream resulting from of gold and aggregate mining, watershed land use, and streamflow regulation and diversion at Saeltzer Dam and Whiskeytown Dam. These activities have drastically altered the flow regime, the channel morphology, and most critically, the physical processes that are essential to creating and maintaining a healthy river channel and healthy habitats, as well as providing the impetus for restoring damaged conditions. Our geomorphic investigations revealed that meaningful geomorphic processes are not initiated at most of our study sites until flows exceed 3,000 to 4,000 cfs (2.2 to 3.0-year flood). A properly functioning alluvial stream should exhibit thresholds to geomorphic processes during a 1.5 to 2-year flood. The reduced magnitude, frequency, and duration of high flows has resulted in profound geomorphic changes in Reaches 1, 3A, and 4, including loss of coarse sediment storage, coarsening of the bed surface, channel incision, riparian berm formation, increased channel stability, loss of functional floodplains, reduced channel complexity, and loss of gravel bars associated with an alternate bar morphology. While fall-run Chinook salmon populations have stabilized over the last few years due to increased baseflows, improvement in geomorphic processes and channel morphology would contribute toward increasing fall-run salmon production from lower Clear Creek. Steelhead and spring-run Chinook salmon should also benefit from improved geomorphic functions.

Remediation of historic impacts should be accomplished by a combination of actions, including increased coarse sediment supply to the stream, improved high flow regime, and channel rehabilitation (Kondolf and Williams, 1999). Channel rehabilitation and gravel introduction efforts are presently underway; recommendations listed in the following sections focus on geomorphic needs, information needs, and adaptive management.

6.1. Recommendation #1: Restore fluvial geomorphic processes

6.1.1. Flow management

Our geomorphic monitoring results suggest that flows exceeding 3,000 cfs to 4,000 cfs are needed in most reaches to initiate geomorphic processes. To address the entire range of high flows and associated geomorphic processes, we present four different classes of high flows and then link different process-based geomorphic objectives (Attributes) to these flow classes (Table 13).

Of the four flow classes described above, we have obtained quantitative measurements for the Small and Moderate classes, and have made qualitative observations for Very Large flows (1997 and 1998 floods). Results of the Small and Moderate high flow classes are summarized in earlier sections of this report. Our observations of the Very Large high flow events suggest that some of the expected geomorphic processes did not occur, particularly channel migration, channel avulsion, and bar formation. These processes were inhibited by riparian encroachment, which discouraged channel movement processes, and by the lack of adequate coarse sediment supply, which likely discouraged bar formation processes. While these Very Large flood processes are important for periodic channel maintenance and rejuvenation, the relatively more frequent Large flood class is also important for discouraging riparian encroachment. Once established, riparian encroachment appears resistant to the post-dam flood regime. The Very Large high flow class still occurs on lower Clear Creek when Whiskeytown Reservoir fills and a spill event is conveyed through the glory hole spillway; however, the Moderate and Large high flow classes have been severely reduced by Whiskeytown Dam. For example, the 10-year flood has been reduced from 18,000 cfs to 10,000 cfs, and the 5-year flood has been reduced from 12,500 cfs to 6,500 cfs.

Table 13. Recommended high flows for Clear Creek below Whiskeytown Dam (with priority needs in italics).

Flow Class	Recommended Magnitude	Recommended Duration	Recommended Timing	Management Target (objective)	Miscellaneous Notes
Small	>1,000 cfs	Relatively longer duration needed (5-10 days)	Occurs during winter tributary runoff events	Attribute 3: Frequently mobilized channelbed surface (sand and pea gravel).	Naturally occurs with adequate frequency but duration could be improved
Moderate	*>3,000 cfs*	*2-4 days*	*Future releases during Average water years*	*Attribute 3: Frequently mobilized channelbed surface (riffles and gravel bars).*	*Needs to occur more frequently*
Large	*>5,000 cfs*	*1-4 days*	*Future releases during Wet and Extremely Wet water years*	*Attribute 4: Periodic scour of alternate bars; Attribute 6: Channel migration; Attribute 7: Floodplain inundation.*	*Needs to occur more frequently*
Very Large	>10,000 cfs	Same as currently occurs (1-2 days)	Occurs during winter uncontrolled spill events	Attribute 4: Periodic scour of alternate bars; Attribute 6: Channel migration and/or avulsion; Attribute 7: Floodplain inundation; Attribute 8: Create and sustain complex mainstem and floodplain morphology.	Uncontrolled spills occur with reduced frequency, but still adequate;

6.2. Recommendation #2: Remove constraints to controlled flow releases

The primary constraint to improving the high flow regime from Whiskeytown Dam is that the controlled outlet works capacity is only 1,200 cfs. The spillway capacity is 23,000 cfs (USBR, 1981), but is only used for uncontrolled spills. In 1999, Reclamation completed an investigation of several structural and operational approaches for improving flows in the 6,000 cfs range. The analysis assumed an arbitrary 7-day flow duration of 6,000 cfs during March of 5 'Wet' years over a 20 year span. The proposed alternatives are summarized in Table 14 (USBR, 1999).

Table 14. Summary of alternatives in USBR Value Planning Study, Lower Clear Creek Hydraulic Analysis at Whiskeytown Dam (USBR 1998).

Alternative	Structural Cost	20-year power loss cost*
1) Add gates on spillway w/flap in throat	$4,600,000	$2,247,000
2) Add gates on spillway	$4,600,000	$2,247,000
3) Operation modification to induce spills	$0	$2,247,000
4) Modify outlet works	$28,000,000	$2,247,000
5) Add additional tunnel outlet	$53,000,000	$2,247,000

*Present worth cost assuming release occurs in March during five wet years over 20 years, cost of power assumed to be $18.00/MWH

Of these five alternatives, Alternative-1 provides the best capability for controlled flow releases and greatest likelihood of success. Alternative 3 provides the lowest cost, but with a reduced ability to control releases to lower Clear Creek. No additional analyses of Whiskeytown Dam have been completed since the initial USBR investigations. We recommend that Reclamation perform additional analyses with Alternatives 1 and 3, focusing specifically on how Alternative 3 would be implemented (operational modeling), and assessing tradeoffs in power losses at various release magnitudes, durations, and timing For example, power losses may be able to be minimized or eliminated if releases occur during wet years when other Reclamation facilities are spilling high flows. Additional analyses should consider shorter duration of high flows (perhaps 1 to 4 days instead of 7 days), as most geomorphic work is done early in the flood hydrograph, and longer duration high flow releases exacerbate coarse sediment loss immediately downstream of Whiskeytown Dam (requiring more gravel to be added mechanically to maintain gravel storage). Shorter duration high flow releases are also more water-efficient, as described in Section 5.5.2.

6.3. Recommendation #3: Continue sediment management program

High flow releases will continue to occur regardless of whether our recommended flow improvements are pursued; therefore the need for gravel augmentation downstream of Whiskeytown Dam will continue. Details of gravel augmentation recommendations are contained in Appendix D. Conceptually, the gravel augmentation program should follow a two-step process: 1) short-term gravel “transfusion” to restore gravel storage in the channel, improve fluvial processes, and increase spawning and rearing habitat, and 2) long-term, periodic gravel augmentation to maintain the storage restored by the short-term transfusion. With an improved gravel supply and high flow regime, gravel would eventually be able to route through the entire river length down to the confluence with the Sacramento River (Figure 43). At the point when storage and routing are restored, gravel would simply be inserted immediately downstream of Whiskeytown Dam at a rate equal to the depletion caused by high flows, thus preserving gravel storage over the entire length of river. Until continuity in sediment transport is achieved, however, multiple introduction sites should be used, including the Peltier Valley Bridge site, Igo Gaging Station site, Reading Bar site, and North State Aggregates site. When monitoring data shows that gravel is routing from an upstream site to a downstream site, gravel introduction at the downstream site can be discontinued. Eventually, gravel introduction should only occur below Whiskeytown Dam.

Fine sediment reduction efforts in the lower Clear Creek watershed, conducted by the Western Shasta RCD, National Park Service, and other agencies, should be continued. Additionally, flow releases greater than 6,000 cfs should begin to cause scour on gravel bars, exposing sand stored in the gravels for downstream transport out of the system. If fine sediment supply is reduced from the watershed, the gravel bar composition after redeposition should contain less fine sediment than prior to the scouring flood. Watershed efforts combined with improved high flow releases from Whiskeytown Dam are complementary, and over time will reduce fine sediment storage in the lower Clear Creek channel. A key flow management strategy for future flood releases would be to provide short duration (perhaps 1-2 day) high magnitude (exceeding 6,000 cfs) flows to scour the bed surface and expose sand grains to fluvial transport, followed by longer duration (perhaps 4 days) small magnitude flow (perhaps 3,000 cfs) to minimize gravel transport rates, maximize sand transport rates, and induce sand deposition on constructed floodplains at the Floodway Rehabilitation Project. As an illustrative example using the bedload transport curves at the Floodway Rehabilitation Project (Figure 42), the curves predict that a flow of 1,000 cfs transports very small amounts of gravel per day, while a flow of 10,000 cfs may transport 1,000 tons per day. Therefore, a higher flow may transport a large rate of sediment, but the short duration minimizes gravel transport. If the high flow is followed by a longer duration and smaller flow that transports lots of sand but no gravel, it reduces the amount of gravel that needs to be replaced while transporting large volumes of fine sediment out of the system. This two-staged flow management approach has been implemented on the lower Colorado River (Webb, et al., 1999), and has been recommended on the Trinity River as well (USFWS, 1999; Wilcock et al, 1995).

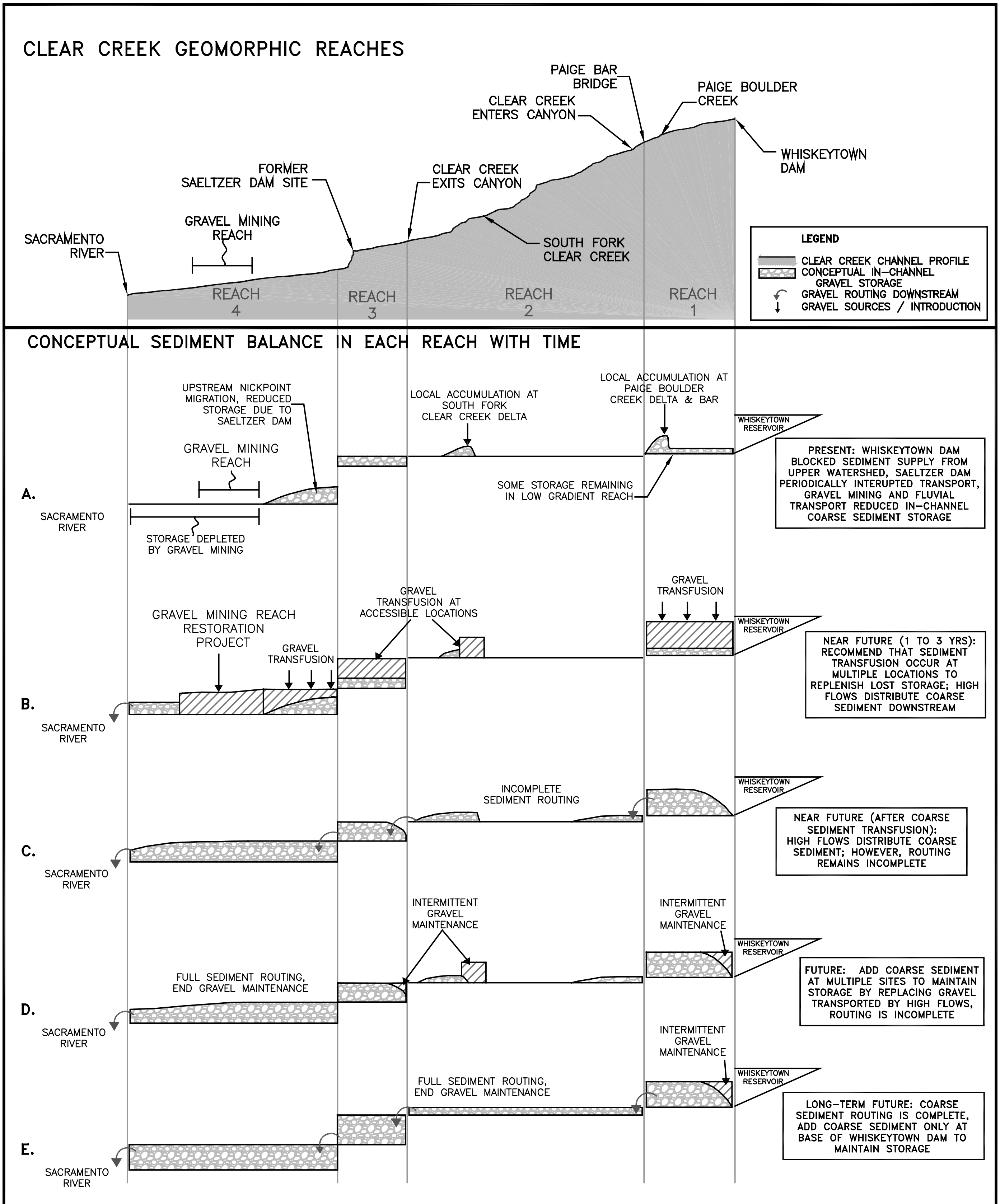


FIGURE 43. LOWER CLEAR CREEK CONCEPTUAL MODEL OF DESIRED FUTURE COARSE SEDIMENT STORAGE & ROUTING CONDITIONS

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6.4. Recommendation #4: Develop an Adaptive Management Program

Adaptive management is a formal, systematic, and rigorous program of learning from the outcomes of management actions, accommodating change, and improving management (Holling, 1978). A functional adaptive management program combines both assessment and management; however, most agency management structures do not allow both to occur simultaneously (International Institute for Applied Systems Analysis, 1979). In situations where adaptive management is being attempted, it is commonly mis-applied by practicing *passive* adaptive management rather than *active* adaptive management. There are two traits of passive adaptive management. The first is to apply a single management action to test a hypothesis or restoration approach, rather than applying several different actions under controlled experimental conditions to evaluate the best approach. For example, passive adaptive management would install riparian plants in the same substrate rather than installing plants in a variety of different (but controlled) substrates. The second component is to rely on *trend* monitoring rather than *process* monitoring. Trend monitoring is when practitioners compare a dependent (y-axis) management variable (e.g., smolt production) with time as the independent variable (x-axis). This treats the causal mechanism(s), such as fish growth or egg-to-emergence success, as a black box, and the turnaround time for improving management usually requires many years. Process-based monitoring, on the other hand, attempts to understand underlying causal mechanisms, which, once established, provides information to resources managers in a timely manner.

Active adaptive management is a preferable approach because it greatly shortens the learning time and management actions. In the above riparian planting example, an active adaptive management approach would place riparian plants in a variety of controlled substrates in a single year (with adequate monitoring), and thereby learn the preferable planting substrate in one year rather than many years. Active adaptive management, using process monitoring, likewise shortens learning time and management improvement time by monitoring causal mechanisms. For example, if higher flows were released and we measured adult returns over time as our dependent variable (trend monitoring), we would rely on a statistical comparison of flow versus adult salmonid escapement to draw conclusions about the effectiveness of our management action (high flows). This feedback loop may require many years to occur, and in the end may still leave considerable uncertainty regarding whether the escapement trend occurred in response to the management action, or to some other factor that was not monitored (e.g., ocean conditions). There are some components to the present monitoring program on lower Clear Creek that will contribute to an active adaptive management program, but much more planning needs to occur to develop a functional adaptive management program.

6.5. Recommendation #5: Develop conceptual models for Clear Creek

An important foundation for an adaptive management program is a sound conceptual model, or models, that cover the entire spatial and temporal scales of the system. Conceptual models are qualitative relationships developed to link different ecosystem variables, such as responses of fish populations to flow, or gravel transport rates to sediment supply from the watershed. These qualitative relationships can be developed to describe how the system functioned naturally, how historical and present management has impaired these relationships, and how these impairments have affected key species or processes. A broad level conceptual model may include a need for a sediment budget, but a finer scale conceptual model is also needed for the relationship of the sediment budget to flows and gravel augmentation. Similarly, a monitoring plan commensurate with the spatial and temporal scales of the conceptual models is also needed for adaptive management. The conceptual modeling approach forces an adaptive management program to understand the inter-workings of the river ecosystem (at least in general terms), and the inter-dependencies of the biota to physical processes. This approach also helps develop hypotheses concerning factors that may limit production or survival of key species. Qualitative conceptual models can then be converted to quantitative predictive models or empirical relationships to evaluate the result of management actions. As mentioned previously, a key component of a successful adaptive management program is that it employs *active* adaptive management; the conceptual modeling approach allows active adaptive management to occur.

Conceptual models of various forms have been prepared for lower Clear Creek; however, these individual conceptual models have not yet been systematically reviewed and incorporated into the Clear Creek Adaptive Management Workgroup. Perhaps the most complete set of conceptual models developed to date are those prepared for the CALFED Adaptive Management Forum (and included in the 2002 CALFED proposal for the Floodway Rehabilitation Project). This set of conceptual models should form the initial framework for additional detailed conceptual models to be developed for lower Clear Creek.

6.6. Recommendation #6: Continue monitoring geomorphic processes

Monitoring is a key component of an adaptive management program, and should include various biotic, geomorphic, and hydrologic components. Rather than discuss the myriad of monitoring needs on lower Clear Creek, we summarize geomorphic monitoring recommendations based on the results of this study.

Future geomorphic monitoring should focus on: 1) reducing the uncertainty in quantitative estimates of thresholds for bed mobility and bed scour that has resulted from the limited data collected during this study; 2) evaluating gravel routing at the gravel introduction sites, and 3) integrating the geomorphic monitoring program associated with the Floodway Rehabilitation Project with the rest of lower Clear Creek.

We recommend that the Peltier Valley Bridge, Reading Bar, and Renshaw Riffle study sites be re-occupied and new bed mobility and scour experiments be installed to monitor future high flow events. This additional information should improve channel maintenance flow recommendations. Additional sample sites could be established at the Igo gaging station (to document thresholds in the Reach 2 canyon) and at the North State Aggregates site (to document thresholds at the upstream end of the Floodway Rehabilitation Project reach). Experiments should target a variety of alluvial deposits, including lee deposits behind boulders, pool tails, spawning riffles, point bars, and others.

The Western Shasta RCD has been using rocks impregnated with radio tracers to monitor mobilization and transport distance of introduced gravels at the former Saeltzer Dam site and immediately downstream of Whiskeytown Dam. These monitoring approaches should be continued in the future to evaluate the degree of gravel routing through the system (see Figure 43), and be supplemented with old-fashioned painted rocks to evaluate thresholds for movement of introduced gravel. Perhaps the most important aspect to document changes in instream gravel storage is to establish long-term monitoring cross sections at a variety of locations in Reach 1, 3A, and 4. The highest intensity of cross sections should be installed in the Peltier Valley Bridge bedload modeling reach (Figure 21) to monitor long-term gravel export from the upstream reach. For example, once the short-term gravel transfusion is complete and gravel storage is restored to the reach, perhaps as many as 20 cross sections should be installed between RM 16.3 to 17.0 to document existing conditions. Then, after a high flow release occurs that is capable of transporting coarse sediment, cross sections should be resurveyed to estimate the net export of gravel from the reach. This volume can then be used to determine gravel introduction rates necessary to replace gravel transported out of this reach by the high flow. This approach is more easily implemented in this reach than bedload sampling with Helley-Smith samplers during high flows. Additionally, mapping steelhead and chinook salmon redds on the 1997 ortho-photo basemaps would be a complementary addition to the gravel introduction monitoring, to correlate changes in spawning distribution with gravel introduction and routing.

Other miscellaneous monitoring suggestions focus on the benefits of fine sediment reduction efforts and improved high flow regime. As discussed above, the combination of reduced fine sediment supply and increased high flows should reduce fine sediment storage in lower Clear Creek. Ideally this reduction in fine sediment storage would occur in salmonid spawning gravels as well, so we suggest establishing gravel quality index sites within our study sites to document long-term changes in fine sediment storage. Different depositional features should be stratified (pool tails, lee deposits, etc.) and sampled in a statistically rigorous way in order to make meaningful evaluations of gravel quality changes. Because improvement in gravel quality will require some degree of bed scour and redeposition, scour cores should accompany the gravel quality monitoring sites. One method combining scour cores and gravel quality monitoring has been successful on the Trinity River (Hales, 1998). As the scour core cylinder is installed into the bed surface (Figure 28), the excavated substrate is collected and retained to document existing particle size distribution. Then, clean tracer gravels are backfilled into the hole and the cylinder removed. After a high flow scours and redeposits the bed surface, the cylinder is re-inserted into the bed at the scour core location, and the redeposited material is excavated down to the top of the tracer gravels and retained for particle size analysis. The particle size distribution of the original material can be compared to that of the redeposited material to evaluate whether fine sediment contribution has decreased. Numerous samples will be required to accommodate the natural variability in particle size distribution, and gravel quality improvements may require a number of high flow releases to reduce fine sediment supply from upstream reaches of the channel. Over time, however, a successful monitoring prograpm would be capable of detecting changes, and then relating those changes back to the initial management action.

6.7. Recommendation #7: Highlight Clear Creek as a showcase for other regulated alluvial rivers

This report recommends flow and sediment management activities intended to restore attributes of healthy alluvial and bedrock reaches. This approach — restoring river ecosystem health by enhancing the underlying geomorphic processes that create a healthy ecosystem — has rarely been attempted on a highly regulated river like Clear Creek. A primary hypotheses that needs to be tested on a highly regulated river is whether a disturbance-influenced, dynamic river ecosystem can be restored, but at a smaller scale than existed in pre-dam conditions. If successful, this approach would represent a long-term rehabilitation strategy for many other highly regulated Central Valley rivers. This approach is attractive because ecological and physical process objectives can be meaningfully satisfied while maintaining the use of water for irrigation and power generation. In other words, if this approach can be shown to be a viable long-term restoration strategy on Clear Creek, it can be put forward as a preferred long-term solution to other highly regulated river. This experiment has been attempted to some degree on the Grand Canyon in 1996, and is being implemented on the Trinity River. Clear Creek offers several advantages that make it more amenable to this approach than other highly regulated rivers, including:

1) Experimental Control. Clear Creek is unique in that the reach downstream of Whiskeytown Dam is short (17 miles), and has few tributaries, so that good experimental control can be provided by high flow releases from the dam. Remediation of the current outlet works constraint (only 1,200 cfs) would allow good experimental control during high flow experiments.
2) Approximately one-half of the stream length is in a confined bedrock canyon, and the other half is a low gradient alluvial reach, enabling researchers to evaluate effects of high flow releases on two types of channel morphologies.
3) Value Planning Study. The Value Planning Study (USBR, 1999) provided important information to begin evaluating the costs and feasibility of improving the controlled high flow release capability from Whiskeytown Dam. Results show that power losses can be minimized if releases occur during wet water years; infrastructure improvement costs can also be minimized.
4) Almost the entire floodway is owned by BLM, and the few remaining parcels may be acquired by BLM in coming years. This foresight by the Clear Creek Restoration Team in acquiring the river

bottom lands now provides the opportunity of testing large-scale river restoration strategies. Moreover, these lands contain large deposits of dredger tailings, which can serve as a long-term gravel source for mitigating the impacts of Whiskeytown Dam on coarse sediment supply.

5) There is no development in the floodway that would be negatively impacted by high flow releases and consequent channel migration, sediment transport, sediment deposition, and riparian growth, thus offering a rare opportunity in which high flows can be intentionally released with no risk of damage to human infrastructure.
6) Short time-frame for implementing restoration. Full restoration of the stream (restoring gravel supply, fixing the last remaining reach impacted by instream gravel mining) is underway, and can be completed within the next three to five years.
7) The recent removal of Saeltzer Dam has improved the ability of coarse sediment to route through the system, and has improved the likelihood of successful steelhead and spring-run chinook salmon re-introduction.
8) Low overall cost:
    - Less than $11 million for all future channel reconstruction work;
    - Increasing outlet works capacity from Whiskeytown Dam could be less than $6 million
    - No water "cost" to the Bay-Delta system because releases would still be delivered to the Bay-Delta; only power generation losses would need to be considered.
    - Costs for gravel introduction needed to increase and maintain coarse sediment supply in the channel can be low because of BLM ownership of dredge tailings. Using BLM-owned tailings would greatly reduce costs, provide a long-term source for the river (perhaps decades to centuries), and avoid impacting the supply of commercial grade aggregate to surrounding communities.

The numerous opportunities and lack of constraints provided by Clear Creek is rare in the Central Valley. Restoring and managing for dynamic fluvial processes to achieve healthy salmon populations under a highly regulated setting can be achieved. A scaled-down morphology could retain much of a river's original integrity if key fluvial processes are explicitly provided. Although such a restoration strategy is an experiment, it may be the most practical solution for recovering regulated river ecosystems and the species that inhabit them.

7. REFERENCES

Aceituno, M. (1985). *Central Valley fish and wildlife management study*. Problem C-9: Restoration of salmon and steelhead in Clear Creek (projected improvement). Sacramento, U.S. Fish and Wildlife Service.

Bair, J. (1999). *The Clear Creek rehabilitation project and borrow sites special status plant survey results*. Prepared by McBain & Trush, Arcata, California for North State Resources, Redding, California. July 30,1999.

Bjornn, T. C. and D. W. Reiser (1991). *Habitat Requirements of Salmonids in Streams. Influences of forest and rangeland management on salmonid fishes and their habitats*. W. R. Meehan. Bethesda, ML, American Fisheries Society. 19: 83-138.

Blake, M.C., D.S. Harwood, E.J. Helley, W.P. Irwin, A.S. Jayko, D.L.Jones (1999). *Geologic Map of the Red Bluff 30'x 60' Quadrangle*, USGS Map No. I-2542.

Brown, L. R. (1996). *Aquatic Biology of the San Joaquin- Tulare Basins, California: Analysis of Available Data Through 1992*. USGS, Denver, CO, 88 pp.

California Department of Water Resources, 1986. *Clear Creek Fishery Study*, Red Bluff, CA.

CALFED (1998). *Strategic Plan for the Ecosystem Restoration Program*. Sacramento, CA, CALFED Bay-Delta Program: 250 pp.

CALFED (1999). *Ecosystem Restoration Program Plan Volume 1 - Ecological Attributes of the San Francisco Bay-Delta Watershed*. Sacramento, CA, CALFED Bay-Delta Program: 535 pp.

Coots, Millard (1971). Unpublished California Department of Fish and Game data, Redding, CA.

Dietrich, W.E. (1987). Mechanics of flow and sediment transport in rive bends, in *River Channels: Environment and Process*, Institute of British Geographers Special Publication #18, Basil Blackwell Scientific Publications, p. 179-227.

Dunne, T., and L. B. Leopold (1978). *Water in environmental planning*. W.H. Freeman and Company, New York, NY.

Edwards, T.K. and G.D. Glysson (1988). Field methods for measurement of fluvial sediments. *USGS Open File Report 86-531*.

Gomez, B. and M. Church (1989). An assessment of bed load sediment transport formulae for gravel bed rivers. *Water Resources Research*, **25**(6): 1161-1186.

Hales, P. (1999). *Bed scour as a function of Shields parameter: Evaluation of a predictive model with implications for river management*. Masters thesis for Department of Geology, Humboldt State University, Arcata, CA, 136 pp.

Holling, C.S. (1977). *Adaptive environmental assessment and management*. John Wiley and Sons, New York.

International Institute for Applied Systems Analysis, 1979. *Expect the unexpected: An adaptive approach to environmental management*, Executive Report 1, Laxenburg Austria, 16 pp.

Kondolf, G.M. and J.G. Williams (1999). Flushing flows: A review of concepts relative to Clear Creek, California, Prepared for USFWS, Red Bluff, CA, 29 pp.

Leopold, L. B., M. G. Wolman, et al. (1964). *Fluvial Processes in Geomorpology*, Dover Publications, New York.

Leopold, L.B., (1970). An improved method for size distribution in stream bed gravel, *Water Resources Research*, Vol. 6, 1357-1366.

Leopold, L. B. (1994). *A View of the River*, Harvard University Press, Cambridge, MA.

Lestelle, L. C., L. E. Mobrand, et al. (1996). *Applied ecosystem analysis-- a primer*, US Department of Energy, Portland, OR.

Lisle, T.E. and R.E. Eads (1991). *Methods to measure sedimentation of spawning gravels*, USFS PSW Research Station, Berkeley, CA.

McBain and Trush (1997). *Trinity River maintenance flow study - Final Report*. Arcata, CA, 316 pp.

McBain and Trush (2000). *Habitat Restoration Plan for the Lower Tuolumne River Corridor*, Prepared for the Tuolumne River Technical Advisory Committee, Turlock, CA, 217 pp.

National Research Council, (1996). *Upstream: salmon and society in the Pacific Northwest*, National Academy Press, Washington DC.

Natural Resource Conservation Service (1997). *Log-Pearson III hydrological analysis* for lower Clear Creek, Unpublished report, Davis, CA.

Parker, G. (1979). Hydraulic geometry of active gravel rivers. *Journal of Hydraulics Division*, American Society of Civil Engineers 105(HY9), 1185-1201.

Parker, G. (1990a) Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic Research*, IAHR, 28(4), 417-436.

Parker, G. (1990b) *The "ACRONYM" series of PASCAL programs for computing bedload transport in gravel rivers*. External Memorandum No. M-220, St. Anthony Falls Laboratory, University of Minnesota, Minneapolis, February, 123 pp.

Pelzman, R. J. (1973). *Causes and possible prevention of riparian plant encroachment on anadromous fish habitat*. Environmental Services Branch, California Department of Fish and Game.

Sawyer, J. and T. Keeler-Wolf (1995). *A Manual of California Vegetation*, California Native Plant Society, Sacramento, CA. 471 pp.

Schumm, S. A. (1977). *The Fluvial System,* Wiley-Interscience, New York, NY.

Segelquist, C. A., M. L. Scott, et al. (1993). Establishment of Populus deltoides under Simulated Alluvial Groundwater Declines, *American Midland Naturalist*, Vol. 130: 274-285.

Stanford, J. A., J. V. Ward, et al. (1996). A general protocol for restoration of regulated rivers, *Regulated Rivers: Research and Management*, Vol. 12, 391-414.

Tietje, W., R. Barrett, et al. (1991). Wildlife diversity in oak riparian habitat: North Central vs. Central Coast California. Symposium on oak woodlands and hardwood rangeland management, Pacific Southwest Research Station, Berkeley, U. S. Forest Service.

USBR (1999). *Lower Clear Creek Hydraulic Analysis at Whiskeytown Dam Final Report*, Denver, Value Planning Study, 44 pp.

USBR (1981). *Project Data*, Water and Power Resources Service, Denver CO.

USFWS (1995). *Draft Anadromous Fish Restoration Plan- A Plan to Increase Natural Production of Anadromous Fish in the Central Valley of California*, Washington DC.

USFWS, (1999). *Trinity River Flow Evaluation Final Report*. Prepared for the US Dept of Interior, Arcata, CA: 400 pp.

United States Geological Survey (1982). *Guidelines for determining flood flow frequency*. Office of Water Data Collection, Reston, VA.

Webb, R.H., T.S. Melis, P.G. Griffiths, and J.G. Elliot (1999). Reworking of Aggraded Debris Fans, in *The Controlled Flood in Grand Canyon, AGU Geophysical Monograph 110*, American Geophysical Union, 37-51.

Western Shasta Resource Conservation District (1996). *Lower Clear Creek Watershed Analysis*, prepared for the United States Bureau of Land Management, Redding, CA.

Western Shasta Resource Conservation District (2000). *Lower Clear Creek Spawning Gravel Restoration Projects, 1997-2000*, prepared for the United States Bureau of Land Management, Redding, CA, 35 pp.

Wilcock, P.R., G.M. Kondolf, A.F. Barta, W.V.G. Matthews, and C.C. Shea (1995). Spawning gravel flushing during trial reservoir releases on the Trinity River: Field observations and recommendations for sediment maintenance flushing flows, *Center for Environmental Design Research report 05-95*, University of California.

Wilcock, P.R. (1997). *A method for predicting sediment transport in gravel-bed rivers*, Johns Hopkins University report, 44 pp.

Williams, J. G. and G. M. Kondolf (1999). *Rehabilitation Concepts for Lower Clear Creek Shasta County, California*, Prepared for USFWS, Red Bluff, CA, 29 pp.

Yoshiyama, R. M., F. W. Fisher, et al. (1998). Historical Abundance and Decline of Chinook Salmon in the Central Valley Region of California, *North American Journal of Fisheries Management*, Vol. 18, 487-521.

8. APPENDICES

8.1. Appendix A. Glossary of terms

TERM	**DEFINITION**
Accretion	Accumulation of groundwater seeping into a stream or river, that increases the surface discharge.
Aggradation	Raising of the channel bed elevation on a reach-wide scale, due to sediment deposition and accumulation.
Aggregate	Commercially mined river-run rock (sand and gravel) extracted and used for road-base, concrete, etc.
Alluvium/Alluvial	Sediment transported and deposited by running water. An alluvial river has bed, banks, and floodplain composed of alluvium. An alluvial deposit is composed of unconsolidated or partially consolidated river-laid material in a stream valley.
Alternate bar	Fundamental geomorphic unit of alluvial rivers, composed of an aggradational lobe or point bar, and a scour hole or pool. A submerged transverse bar connects adjacent point bars to form a riffle. An alternate bar sequence, composed of two alternate bar units, is a single meander wavelength, usually 9-11 bankfull channel widths long.
Anadromous	Typical life cycle of salmon, in which fish spawn in freshwater streams and migrate early in their life cycle to the ocean where they grow and mature. Anadromous fish return to freshwater as adults to spawn in the stream or river of their origin, then typically die.
Ascending limb	Component of a winter or spring snowmelt hydrograph in which the discharge rapidly ramps up from a baseflow level to the peak flow magnitude.
Avulsion	Large-scale channel abandonment and planform readjustment resulting from large floods.
Bankfull channel	Channel of an alluvial river that contains without overflow approximately the discharge that occurs, on average, once every 1.5 to 2 years.
Bankfull discharge	Flood discharge that exceeds the capacity of the bankfull channel and begins to spill onto the floodplain. Bankfull discharge occurs with a frequency ranging between 1.5 and 2 years.
Bar face	Portion of point bar that is downward - sloped from the floodplain towards the low water edge.
Bedload	Coarse component of sediment transported by a stream. During transport, particles are in constant or frequent contact with the stream bottom. Bedload makes up most of the channel bed and banks of alluvial rivers, but typically represents only 5-15 percent of the total sediment yield (excluding dissolved component).

Boundary shear stress	Force exerted on the channel bed by flowing water. When boundary shear stress (force) exceeds the forces of a particle resisting motion (e.g., particle size and density), the particle may become mobilized and transported downstream.
Braided channel	Channel form having multiple low-flow threads.
Capacity (channel)	Volume of flow a channel can convey before overflowing the channel and spilling onto the floodplain.
Capacity (flow)	Maximum amount of sediment a river can transport, for a given flow condition.
Capillary fringe	Zone in which water is drawn into soil pores above the water table by surface tension (capillarity).
Channelization	Straightening of a river channel or containment between levees.
Channel morphology	The shape, size, and particle size of a channel created by the interaction of fluvial, biological, and geomorphic processes.
Channel slope	Longitudinal slope or gradient of the channel, measured, for example, by the water surface elevation or from the crest of successive riffles.
Competence	A measure of overall stream power, determined by the largest grain size the river can transport, for a given flow condition.
Constriction	Significant narrowing of the channel width, forcing flow between banks.
Conveyance	Ability of a channel to pass water downstream.
Critical Habitat	(1) Specific areas within the geographic area occupied by a species at the time it is listed in accordance with the Federal Endangered Species Act (ESA); (2) Specific areas outside the geographical area occupied by a species at the time it is listed under ESA if there is a determination that such areas are essential for conservation of the species.
Critical rooting depth	Minimum root depth that is capable of anchoring a plant firmly enough to withstand channelbed scour.
Descending Limb	Component of a winter or spring snowmelt hydrograph in which the discharge rapidly ramps down (descends) from a peak flow magnitude to a lower flow.
Degradation	Downcutting of the channelbed elevation on a reach-wide scale, caused by an imbalance in sediment supply and transport processes.
Deposition	Process in which a sediment particle in transport comes to rest on the stream bottom, point bar, floodplain, etc., when the competence and transport capacity of a stream are exceeded by the particle's resisting forces.
Designated Floodway	River channel and adjoining floodplains and terraces that together provide the necessary lateral space (valley width) to convey floods of a specified (designed) magnitude.
Drainage basin	Area of land that drains water, sediment, and dissolved materials to a common outlet along the stream channel. Synonymous with "watershed" and "catchment."

Encroachment	(see Riparian encroachment)
Entrainment	The initiation of motion of sedimentary particles, leading to sediment transport and deposition.
Entrenchment	Ratio of flood-prone channel width to the bankfull channel width.
Exceedance probability (P)	Statistical estimate of the likelihood or probability that a certain discharge will be equaled or exceeded in any given year.
Flood Frequency Curve	The statistical distribution of the annual peak flood discharge for a period of record for a gauging station, typically plotted as discharge verses exceedance probability on a log-probability scale.
Floodplain	Geomorphic surfaces bordering a river channel constructed by the deposition of alluvial material, and inundated by discharges equaling or exceeding bankfull discharge. Floodplains often provide habitat for riparian vegetation.
Floodway	River channel and adjoining floodplains and terraces that together provide the necessary lateral space (valley width) to convey floods of a range of magnitudes.
Fluvial	Processes involving the physical properties of flowing water.
Flushing flows	High-flow dam releases intended to “flush” fine sediments stored in the bed of rivers and transport them downstream, thus cleaning the riverbed. Flushing flows rarely achieve their goal, as most fine sediments are simply redeposited in the downstream channel bed.
GIS	Geographical Information System. A specialized form of computerized, geographically-referenced data bases that provide for manipulation and summation of geographic data. A GIS may also be defined as a system of hardware, software, data, and personnel for collecting, storing, analyzing, and disseminating information about geographical areas.
Groundwater	The saturated subsurface or phreatic zone of water, constituting 21% of the world’s fresh water and 97% of all the unfrozen fresh water on earth.
Headward erosion	Process of channelbed erosion or migration upstream from an abrupt drop in the longitudinal profile of a stream.
Hydraulic geometry	The relationship between a given discharge and the physical dimensions of channel, including width, depth, velocity, and slope.
Hydraulic Radius (R)	Hydraulic mean depth, expressed as the ratio of cross-sectional area to wetted perimeter of the channel (A/p).
Hydrograph	Streamflow (discharge) plotted as a function of time. Annual hydrographs show streamflow during and entire year, typically with daily flow averaged, while flood hydrographs may use time increments of 15 minutes or 1 hour for the duration of the flood.
Incision	Vertical erosion or downcutting of the channelbed.
Knickpoints	Abrupt changes or local perturbations in the longitudinal gradient of a river or stream, caused by accumulation of coarse debris or sharp change in the erosional resistance of the bedrock.

Levee	An engineered berm or dike designed and constructed to confine floodwaters to a specified river corridor, thus protecting adjacent lands from flood inundation.
Longitudinal Profile	The morphology and gradient of a river or stream channel, viewed longitudinally from upstream to downstream.
Meander	The approximately sinusoidal planform pattern of a river or stream channel in which the ratio of channel length to down-valley distance exceeds 1.5.
Meander Belt	River corridor within which channel migration occurs, indicated by abandoned channels, oxbow lakes, and accretion topography.
Migration (channel)	The process in which rivers change their planform location by the gradual erosion of banks, floodplains, and terraces on the steep, outside portion of the meander bend, with concurrent deposition on the inside portion or point bar.
Mitigation	Activities designed to avoid, minimize, rectify, reduce, or compensate for project or land-use impacts.
Morphology	(see Channel morphology)
Particle facies	A discrete patch or zone of homogenously-sized sediments resulting from natural segregation of particle grain sizes within depositional sites.
Phenology	Biological periodicity (e.g. flowering, seed dispersal, etc.) related to climate, especially seasonal changes.
Planform	Allignment or location of a river viewed from directly above, such as a map view.
Plant assemblage	Group of plant species that form a distinct unit, called a stand, in the vegetation mosaic.
Plant recruitment	Plants that have survived through establishment to reach sexual maturity.
Plant stand	A plant assemblage defined by the presence of one dominant species or co-dominance between a few species
Pools	Geomorphic channel forms (or habitat units) characterized by deep water and flat water surface, formed by scouring of the channel bed.
Rating Curve	Graph plotting discharge verses the water surface elevation, to establish a linear or power regression relationship, then used to predict discharge at any given water surface stage height.
Riparian	The zone adjacent to water bodies, watercourses, and surface-emergent aquifers (springs, seeps, and oases) whose water provides soil moisture significantly in excess of that otherwise available through local precipitation. Vegetation characteristic of this zone depends on the availability of excess water.
Riparian Corridor/Zone	The zone of interaction along a river or stream containing moisture-dependent vegetation, trees, brush, grasses, sedges, etc., that affect the channel and are affected by it.

Receding limb	Component of storm, snowmelt, or dam-release hydrograph that is ramping down from a peak flow magnitude to a lower flow.
Recurrence Interval (T)	The average interval (in years) between flood events equaling or exceeding a given magnitude. Defined as the inverse of the exceedance probability (1/P)
Riffles	Shallow, steep, coarse section of river channel, or topographic high in the longitudinal profile, formed at the cross-over of the sediment transport path (transverse bar) and the water flow path.
Riparian berm	Dune of sand deposited along the edge of the low water channel caused by, then anchored by, encroached riparian vegetation. Riparian berms constrict the channel, isolating the channel from adjacent floodplains, often causing the channel to downcut.
Riparian encroachment	The process of riparian initiation, establishment, and maturity progressing toward the low water channel. Reduction in high flow regime reduces natural flood - induced riparian mortality, which allows riparian vegetation to initiate and survive in channel locations that would normally be scoured by floods.
Riparian establishment	Begins at the end of the first summer and extends through several growing seasons as the plant increases energy reserves and strengthens roots and shoots.
Ramping	Flow reduction by either natural or dam control means.
Riparian initiation	Begins at seed germination and extends through the first summer.
Riparian maturity	Period of life-cycle when a plant first expends energy on sexual reproduction and continues through its maximum reproductive period.
Rooting depth	The maximum depth that a plant's roots grow every year.
Sapling	A young tree with a trunk less than 4 inches in diameter at breast height (4.5 feet above the ground surface).
Scour Channel	A secondary channel located on the floodplain, only accessed by the river during flows above the bankfull stage. ##Needs more…
Sediment budget	Quantification of sediment yield to a river channel from different contributing sources, including overland flow and gullying, landsliding, bed and bank erosion.
Sediment deposition	The termination of motion or settling-out of sedimentary particles, usually as result of a decrease in flow capacity and competence in the recession stage of a storm hygrograph.
Sediment load	The rate of sediment transported by a river, expressed in tons per day.
Sediment transport	Process or rate of movement of sedimentary particles downstream by entrainment resulting from physical forces of water acting on the channel bed.
Sediment yield	Annual production of bedload and suspended load contributed to, and transported by a stream or river as result of erosional processes, expressed as tons per year
Seedling	A plant shortly after seed germination, includes the first plumuoles.

Sinuosity	The irregular, meandering planform pattern of a river, strictly defined as a ratio of the length of the channel axis or thalweg to the straight-line length of the river valley (Sinuosity Index).
Slough	Portion of abandoned channel or meander cutoff that continues to receive flow from the main channel
Snowmelt hydrograph	The annual spring flood (long duration, moderate magnitude) resulting from the seasonal melting of snow at higher elevations.
Special Status Species	Generally refers to species with declining populations, including, but not limited to species listed or proposed for listing as threatened or endangered under the state and federal Endangered Species Acts.
Stage (height)	Elevation of the water surface at a particular discharge.
Subsurface particles	Particles found in the gravel column deeper than one D84 diameter below the bed surface.
Surface particles	Particles found in the gravel column from the bed surface to a depth of one D_{84} diameter.
Suspended load	The finer portion of the annual sediment load, transported in suspension above the bed surface
Thalweg	The deepest portion of the channel.
Threatened species	Any species of plant or animal likely to become endangered within the foreseeable future throughout all or a significant portion of its natural range.
Transverse bar	Depositional channel feature representing the path of sediment transport connectivity between two alternating point bars, and location of a riffle.
Turbidity	Cloudiness in water produced by presence of suspended sediments.
Vegetation	Mosaic of different assemblages of plants across a landscape, and wide range of environmental conditions and gradients.
Water yield	Total volume of runoff generated by a watershed over a water year, usually expressed in acre-ft.
Wetlands	A zone periodically or continuously submerged or having high soil moisture that has aquatic and /or riparian vegetation components and is maintained by water supplies significantly in excess of those otherwise available through local precipitation.
Wetted perimeter	Distance from the left edge to right edge of water surface measured along the channel sides and bottom, perpendicular to the flow direction, i.e., along a cross section.

8.2. Appendix B. Summary of coarse (>2mm) and fine (<2mm) bedload transport estimates for WY 1998-2000

Appendix B

CLEAR CREEK near IGO

COARSE BEDLOAD DISCHARGE > 2 mm (tons/day), WATER YEAR OCTOBER 1997 TO SEPTEMBER 1998

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	23.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	7,862	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	10,478	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	448	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	14.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	28.3	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	0.0		0.0	0.0		0.0		0.0		0.0	0.0	
TOTAL (tons)	**0.0**	**0.0**	**0.0**	**0.0**	**18,831**	**28.3**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

WATER YEAR 1998 TOTAL: **18,859 tons**

Appendix B

CLEAR CREEK near IGO

FINE BEDLOAD DISCHARGE < 2 mm (tons/day), WATER YEAR OCTOBER 1997 TO SEPTEMBER 1998

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	14.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	6,368	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	8,662	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	177.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	4.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	8.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	13.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.1	1.3	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.1	21.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	0.0		0.0	0.0		0.0		0.0		0.0	0.0	
TOTAL (tons)	**0.0**	**0.0**	**0.0**	**5.3**	**15,258**	**22.8**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

WATER YEAR 1998 TOTAL: **15,286 tons**

Appendix B

CLEAR CREEK near IGO

COARSE BEDLOAD DISCHARGE > 2 mm (tons/day), WATER YEAR OCTOBER 1998 TO SEPTEMBER 1999

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	1.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL (tons)	**0.0**	**0.8**	**0.0**	**0.0**	**2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

WATER YEAR 1999 TOTAL: **2.4 tons**

Appendix B

CLEAR CREEK near IGO

FINE BEDLOAD DISCHARGE < 2 mm (tons/day), WATER YEAR OCTOBER 1998 TO SEPTEMBER 1999

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.00	4.53	0.00	0.00	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.00	4.30	0.00	0.00	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.00	0.02	0.00	0.00	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.00	0.01	0.00	0.00	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.00	0.00	0.00	0.01	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.00	0.01	0.00	0.00	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.00	0.02	0.00	0.00	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.00	0.01	0.00	0.00	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.00	0.01	0.00	0.00	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.67	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
23	0.0	2.4	0.0	0.04	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.00	0.00	0.44	0.00	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.00	0.01	0.13	0.00	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.00	0.00	0.01	0.00	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.00		0.00	0.00	0.0	0.0	0.0	0.0	0.0
30	0.0	0.1	0.0	0.00		0.00	0.00	0.0	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.00		0.00	0.00	0.0	0.0	0.0	0.0	0.0
TOTAL (tons)	**0.0**	**2.4**	**0.1**	**0.7**	**9**	**0.6**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

WATER YEAR 1999 TOTAL: **12.8 tons**

Appendix B

CLEAR CREEK near IGO

COARSE BEDLOAD DISCHARGE > 2 mm (tons/day), WATER YEAR OCTOBER 1999 TO SEPTEMBER 2000

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000
TOTAL (tons)	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

WATER YEAR 2000 TOTAL: **0.000 tons**

Appendix B

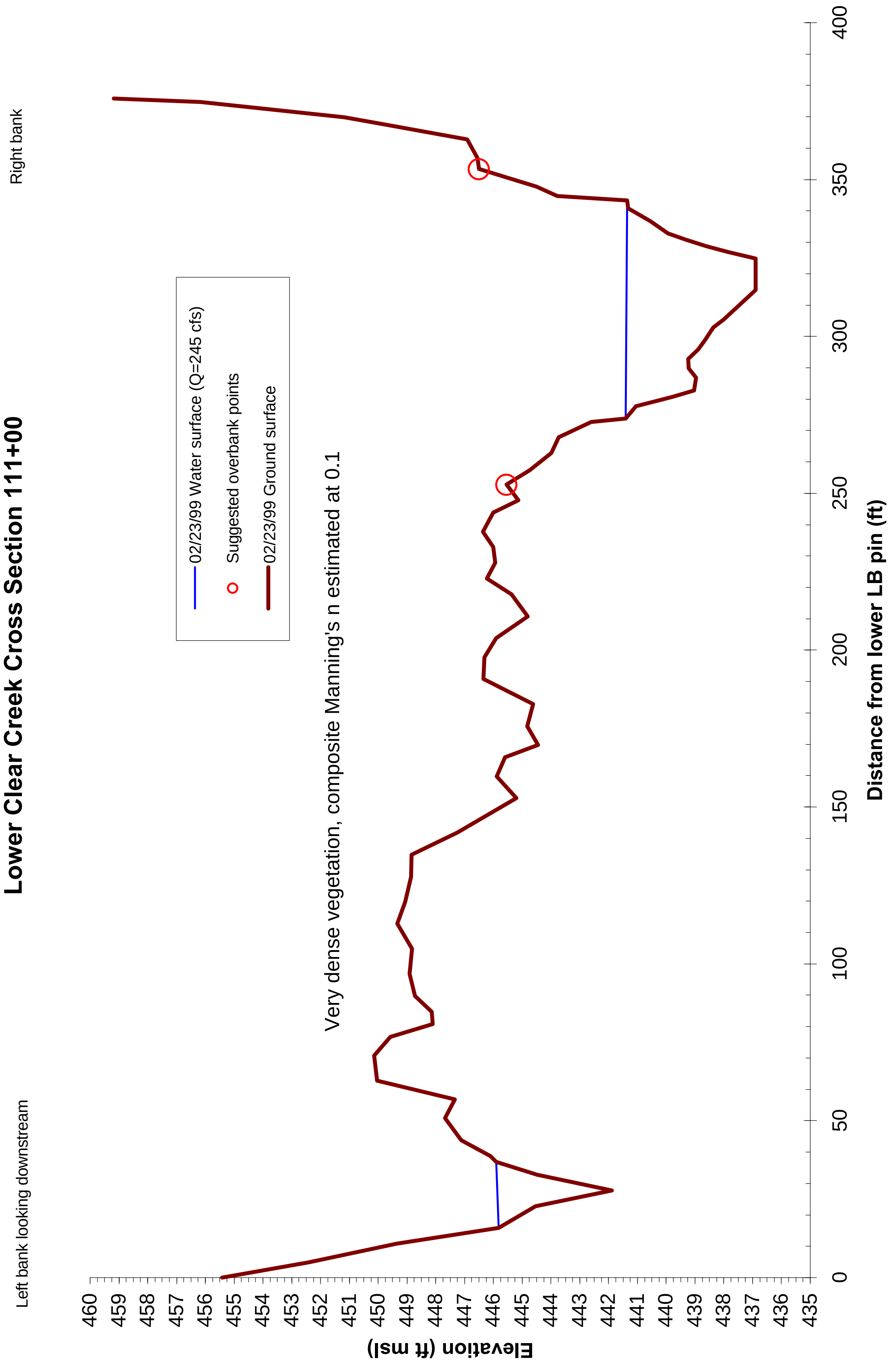
CLEAR CREEK near IGO

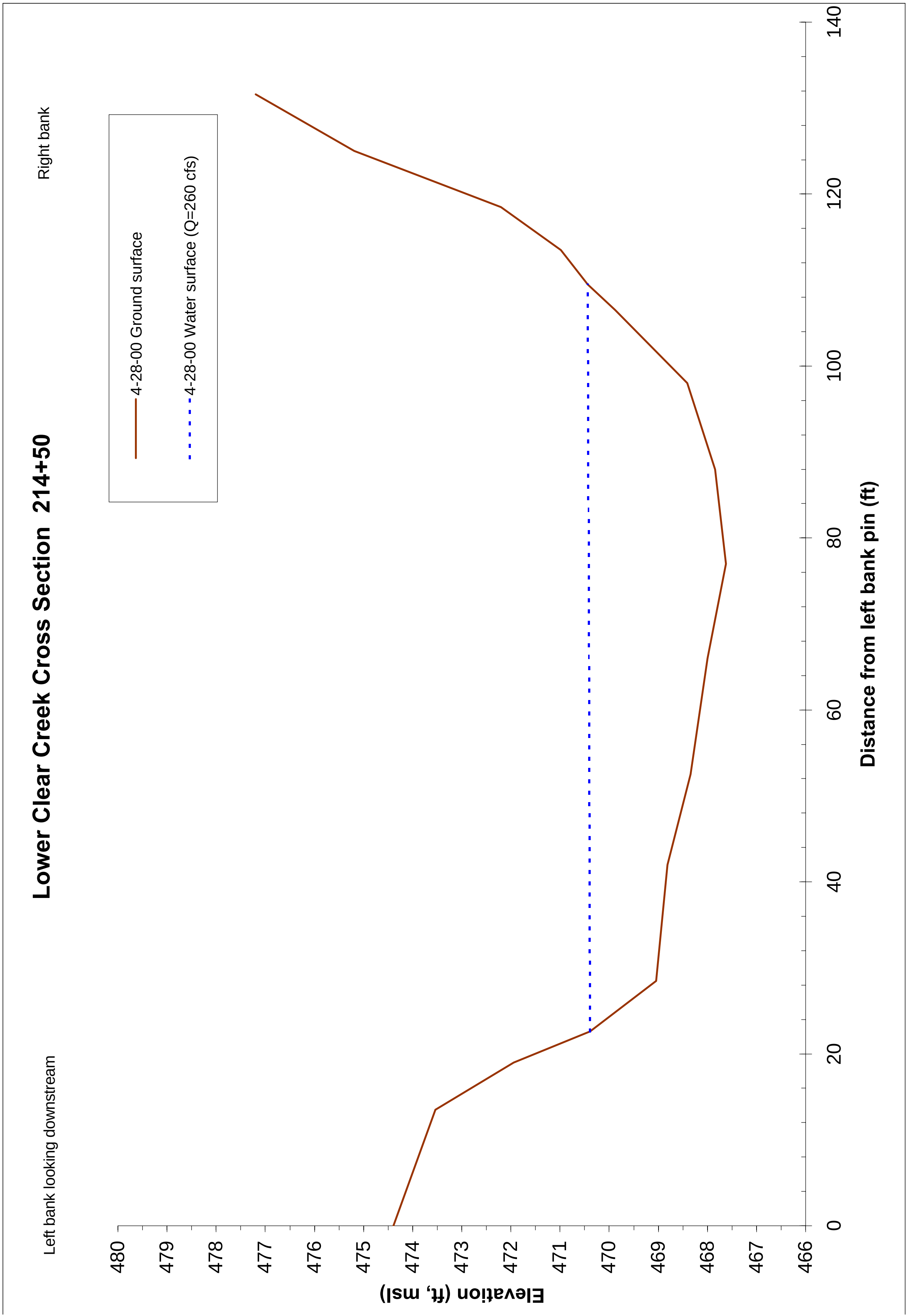
FINE BEDLOAD DISCHARGE < 2 mm (tons/day), WATER YEAR OCTOBER 1999 TO SEPTEMBER 2000

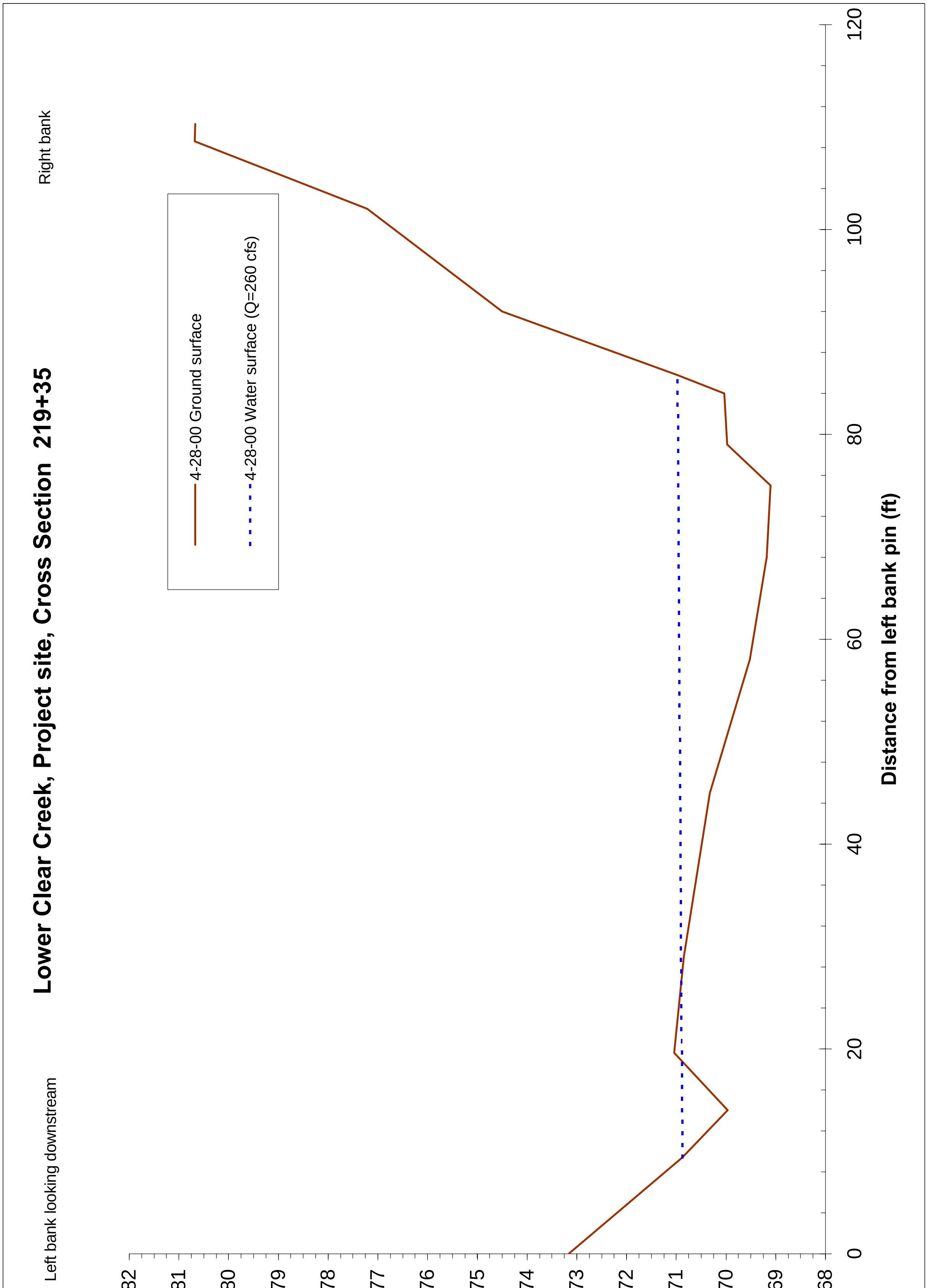
DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	0.000	0.000	0.000	0.000	0.000	0.038	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.011	0.013	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.005	0.008	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.001	0.009	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.039	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.029	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.003	0.012	0.000	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.319	0.017	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.204	0.007	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	2.120	0.003	0.000	0.000	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	1.340	0.001	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.021	0.001	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.001	0.005	0.001	0.000	0.000	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.002	0.000	0.018	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.001	0.000	0.002	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.002	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.001	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.441	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.199	0.000	0.000	0.000	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.003	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.003	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.001	1.260	0.000	0.000	0.000	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000	0.369	0.000	0.000	0.000	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000	0.031	0.000	0.000	0.000	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000	1.391	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TOTAL (tons)	**0.0**	**0.0**	**0.0**	**0.0**	**7.7**	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

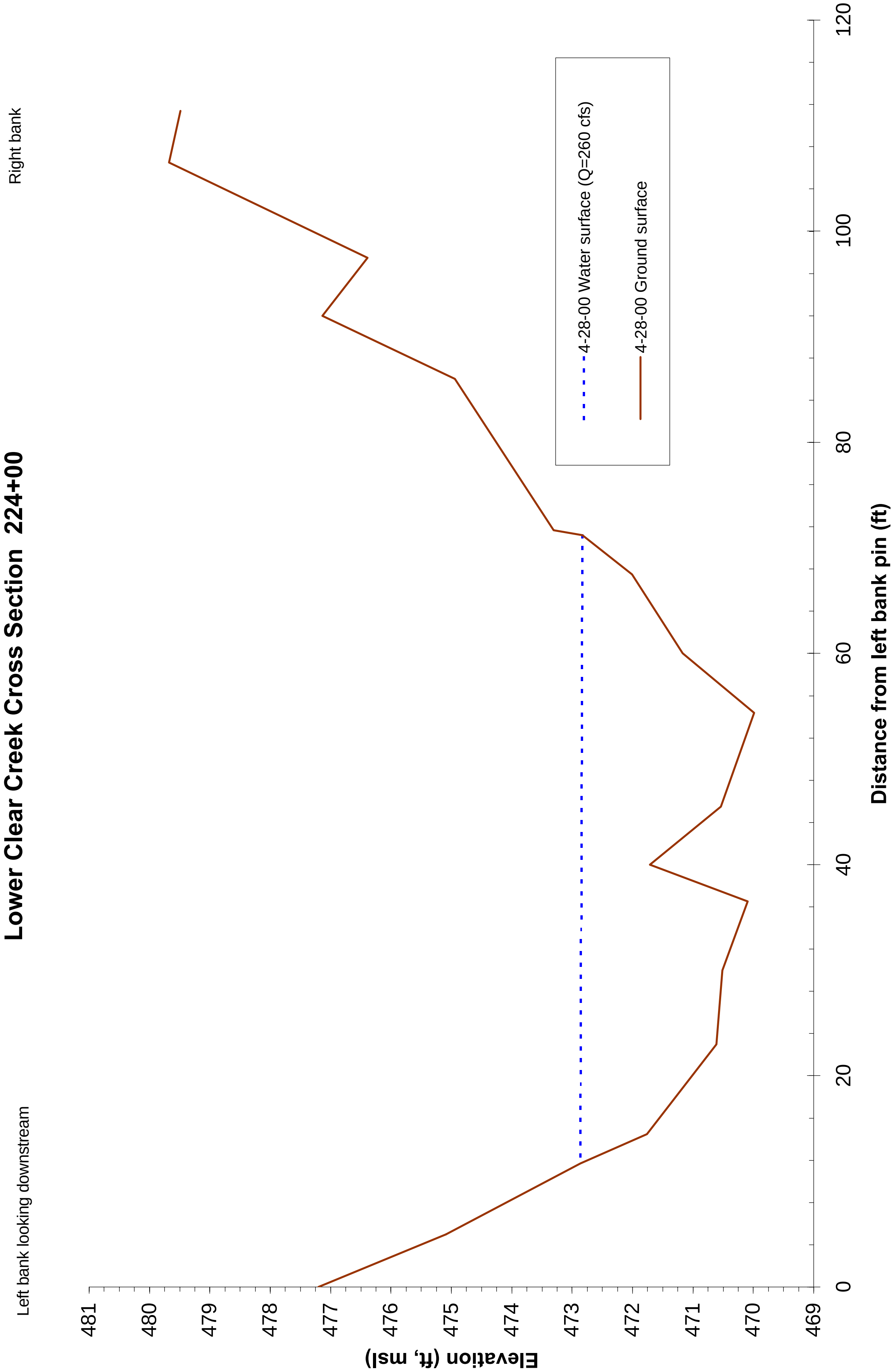
WATER YEAR 2000 TOTAL: **7.98 tons**

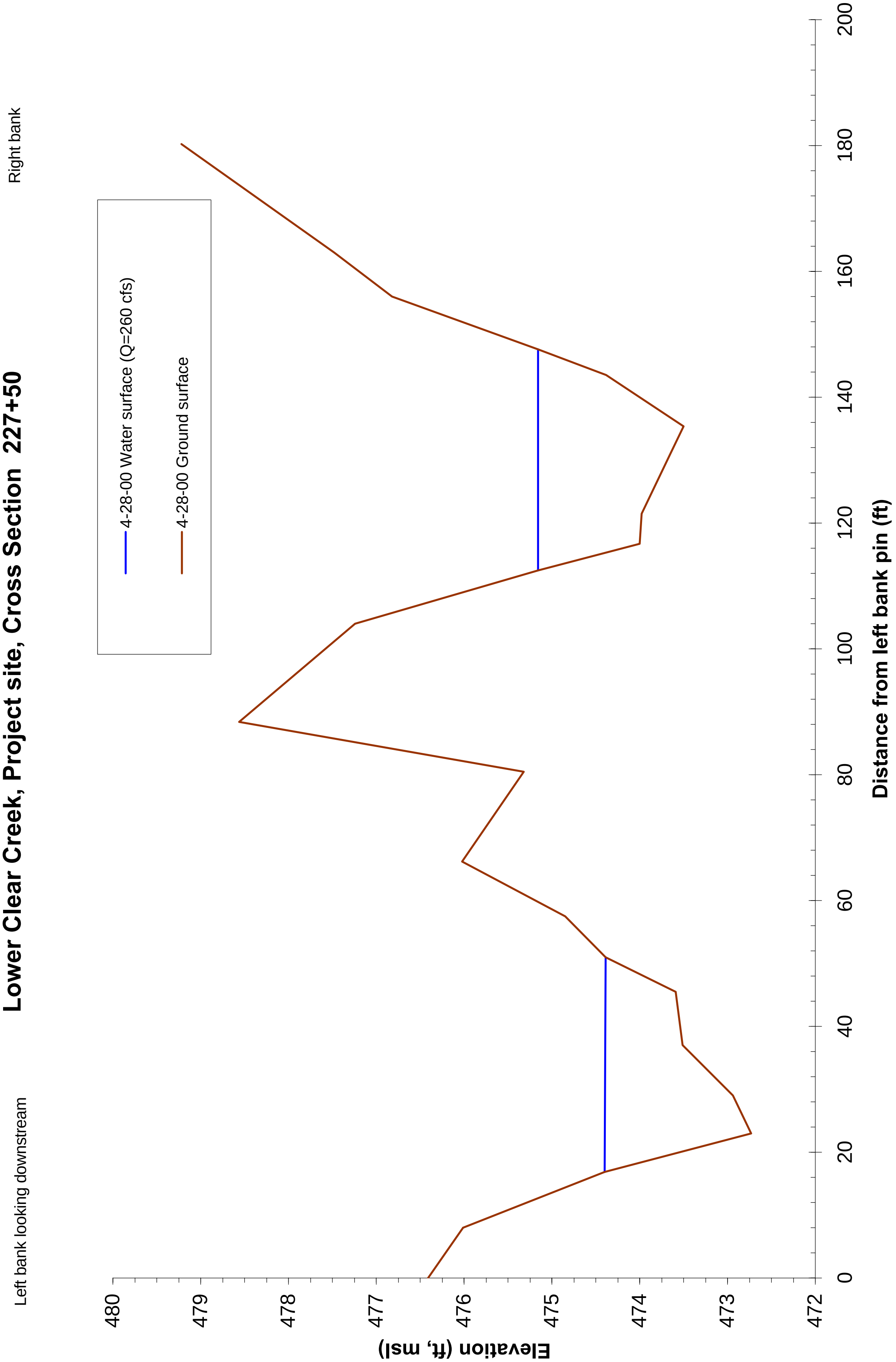
8.3. Appendix C. Clear Creek cross section surveys, surface pebble count data, and bulk sample data

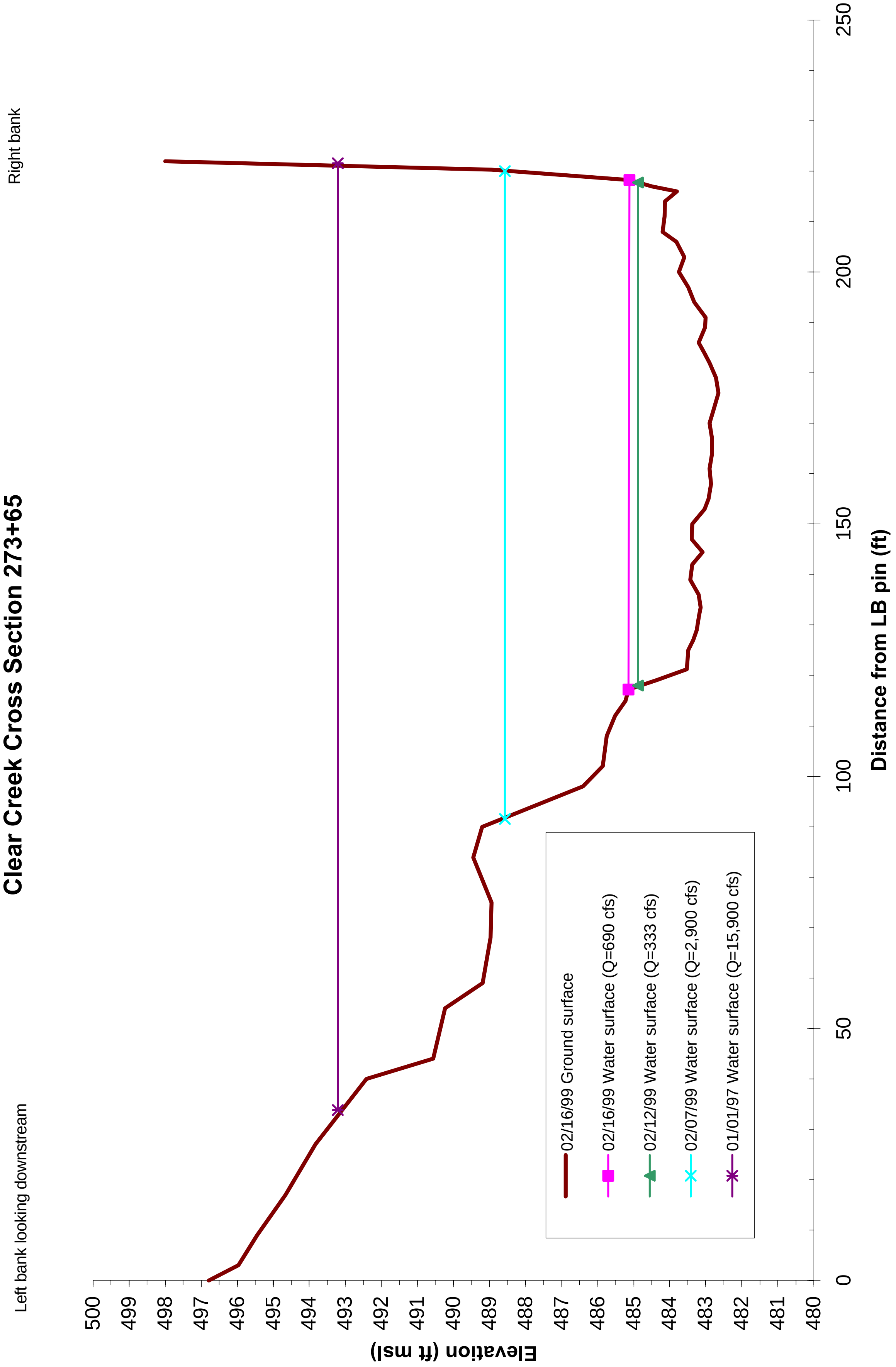

Lower Clear Creek Cross Section 111+00
Left bank looking downstream
Right bank
02/23/99 Water surface (Q=245 cfs)
Suggested overbank points
02/23/99 Ground surface
Very dense vegetation, composite Manning's n estimated at 0.1
Elevation (ft msl)
460
459
458
457
456
455
454
453
452
451
450
449
448
447
446
445
444
443
442
441
440
439
438
437
436
435
Distance from lower LB pin (ft)
0
50
100
150
200
250
300
350
400

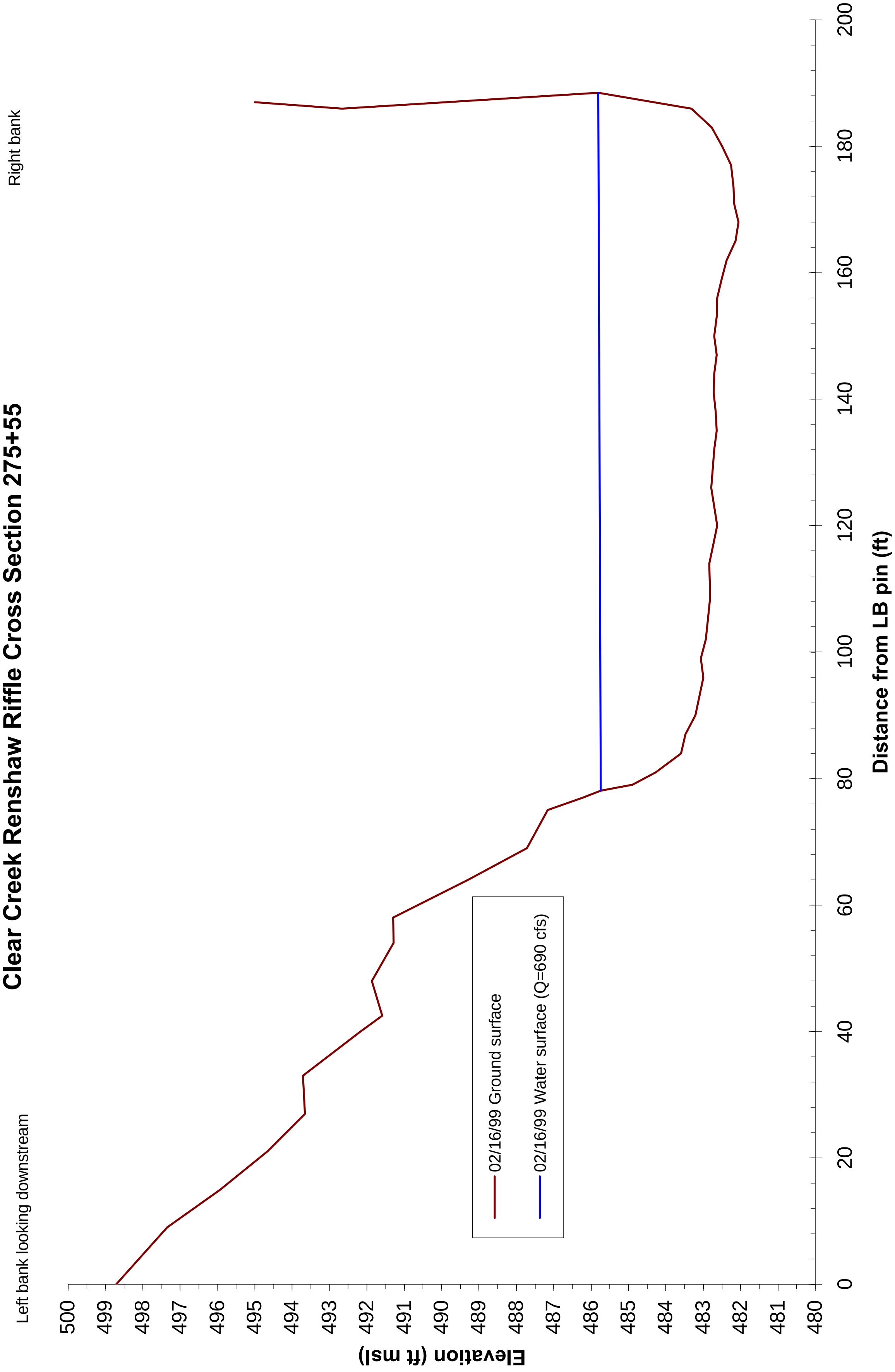

Lower Clear Creek Cross Section 214+50
Left bank looking downstream
Right bank
4-28-00 Ground surface
4-28-00 Water surface (Q=260 cfs)
Elevation (ft, msl)
480
479
478
477
476
475
474
473
472
471
470
469
468
467
466
Distance from left bank pin (ft)
0
20
40
60
80
100
120
140


Lower Clear Creek, Project site, Cross Section 219+35
Left bank looking downstream
Right bank
4-28-00 Ground surface
4-28-00 Water surface (Q=260 cfs)
Elevation (ft, msl)
482
481
480
479
478
477
476
475
474
473
472
471
470
469
468
Distance from left bank pin (ft)
0
20
40
60
80
100
120

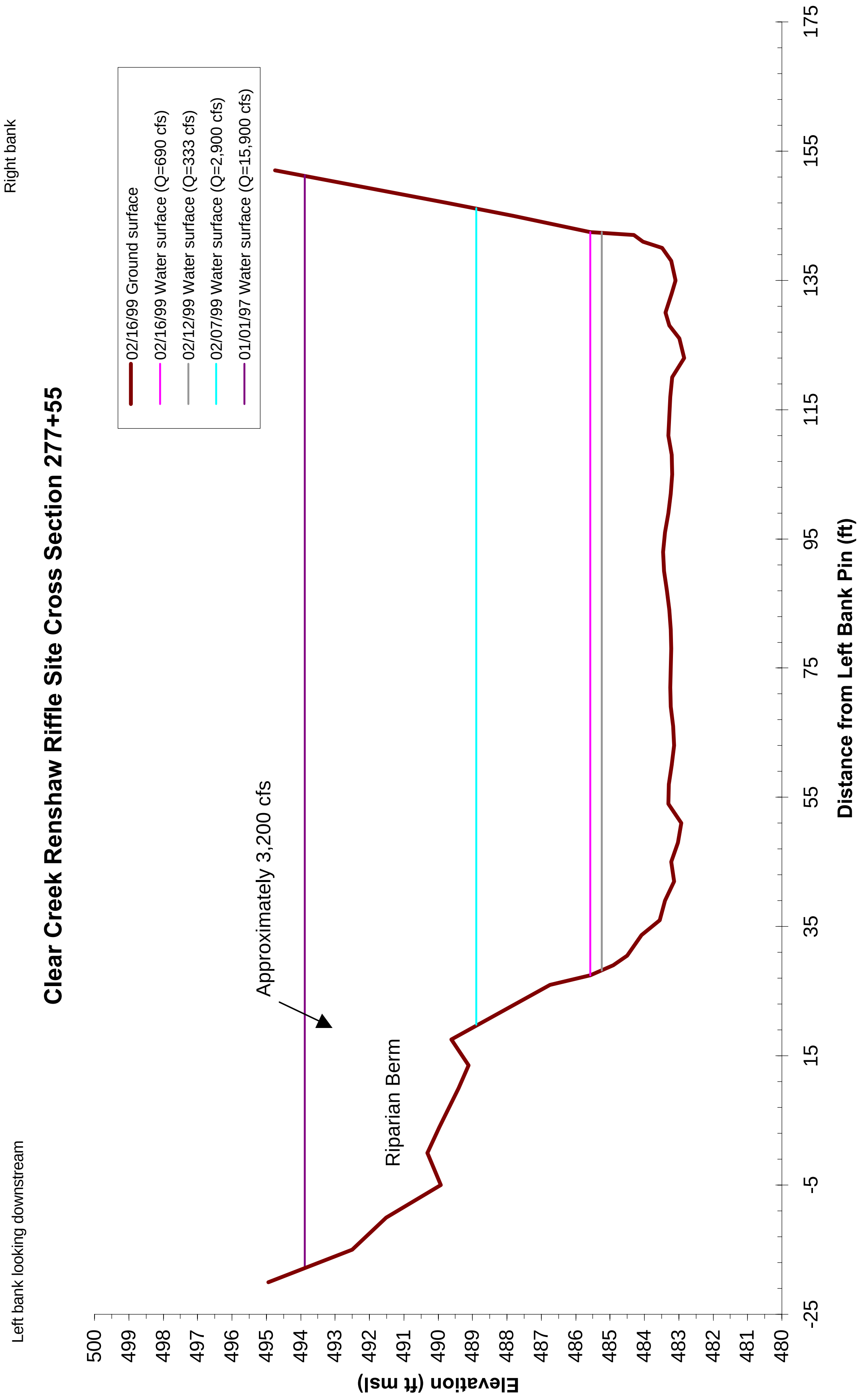

Lower Clear Creek Cross Section 224+00
Left bank looking downstream
Right bank
4-28-00 Water surface (Q=260 cfs)
4-28-00 Ground surface
Elevation (ft, msl)
481
480
479
478
477
476
475
474
473
472
471
470
469
Distance from left bank pin (ft)
0
20
40
60
80
100
120


Lower Clear Creek, Project site, Cross Section 227+50
Left bank looking downstream
Right bank
4-28-00 Water surface (Q=260 cfs)
4-28-00 Ground surface
Elevation (ft, msl)
480
479
478
477
476
475
474
473
472
Distance from left bank pin (ft)
0
20
40
60
80
100
120
140
160
180
200

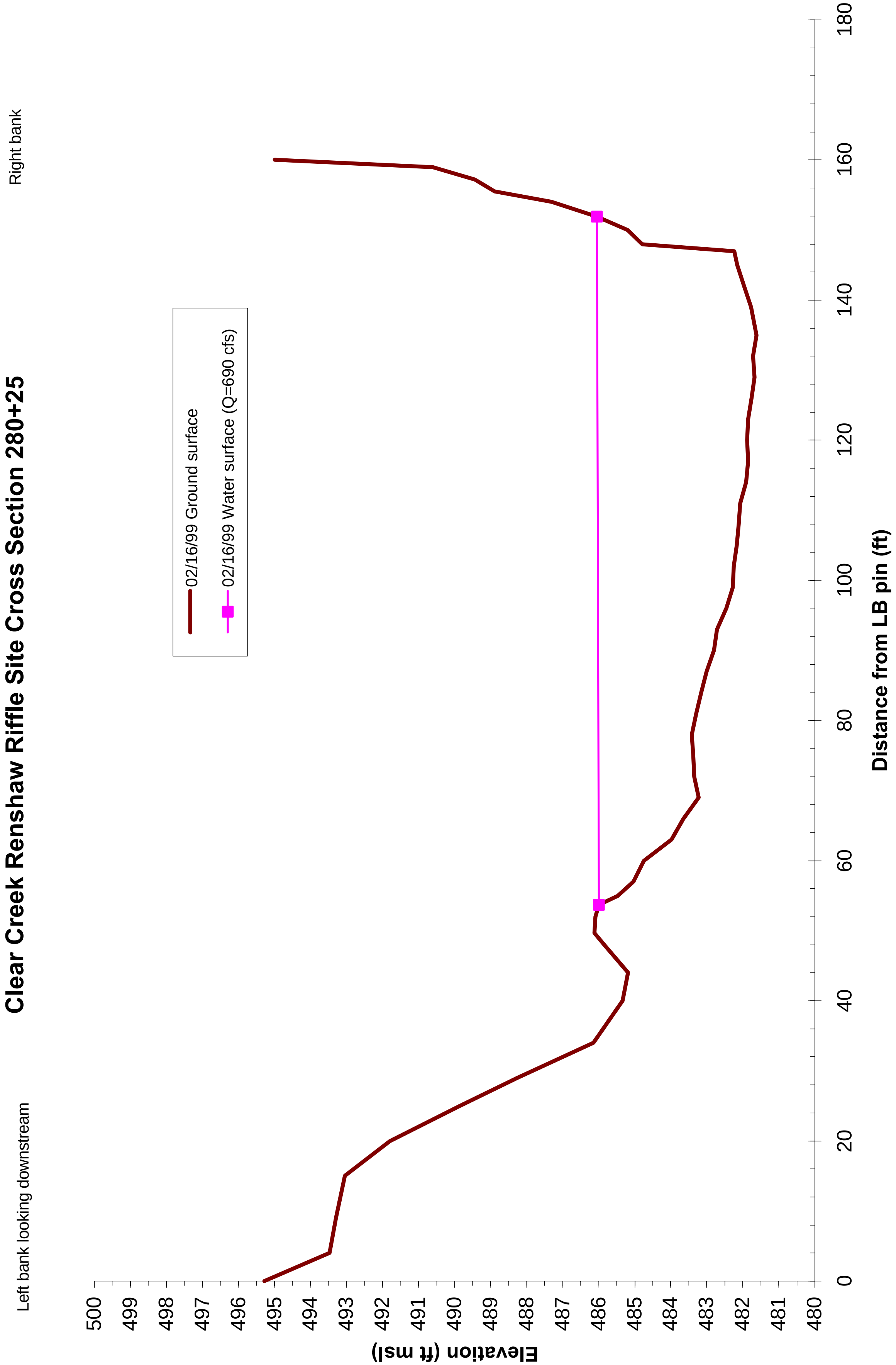

Clear Creek Cross Section 273+65
Left bank looking downstream
Right bank
Elevation (ft msl)
500
499
498
497
496
495
494
493
492
491
490
489
488
487
486
485
484
483
482
481
480
Distance from LB pin (ft)
0
50
100
150
200
250
02/16/99 Ground surface
02/16/99 Water surface (Q=690 cfs)
02/12/99 Water surface (Q=333 cfs)
02/07/99 Water surface (Q=2,900 cfs)
01/01/97 Water surface (Q=15,900 cfs)



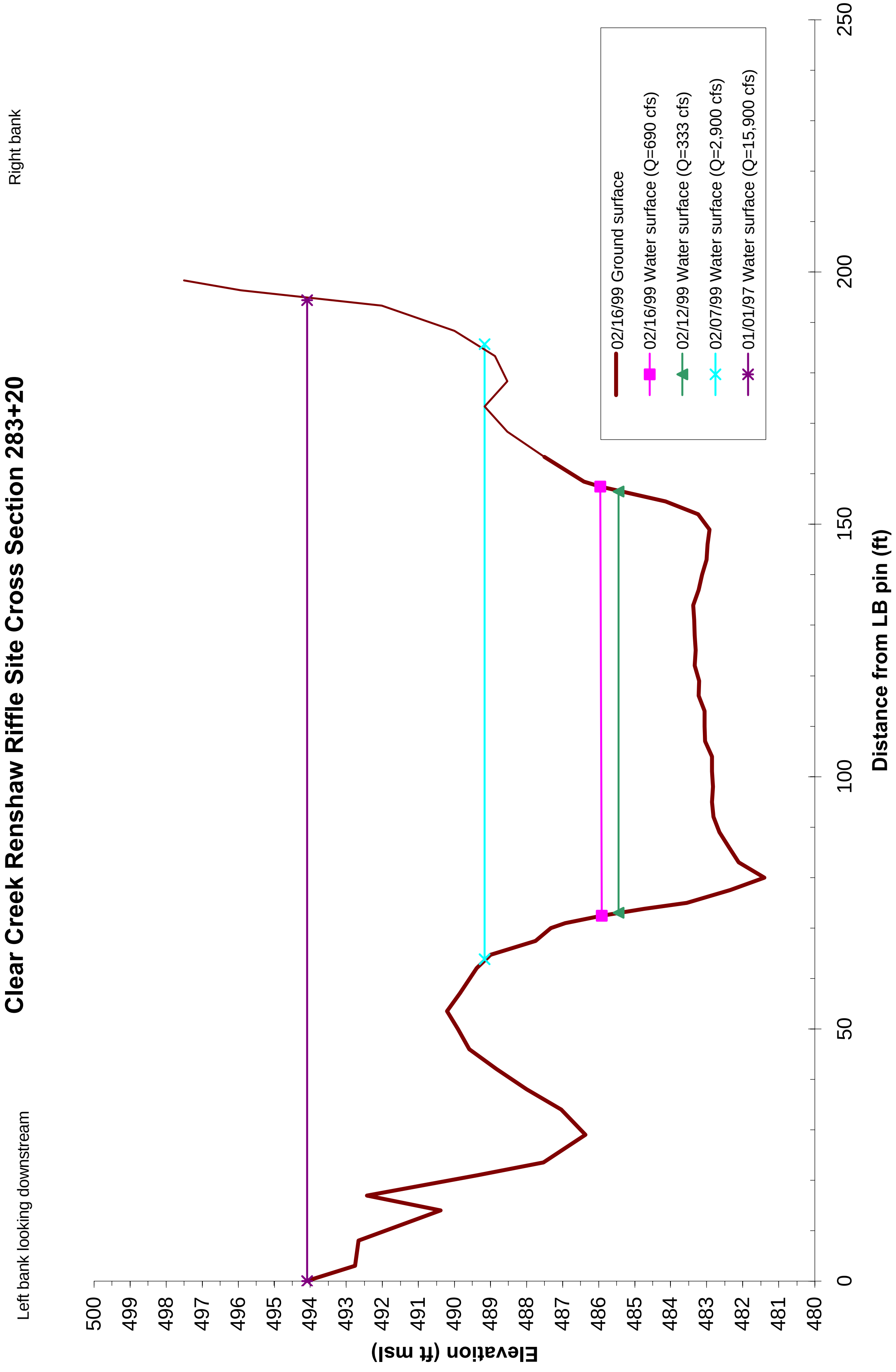
Clear Creek Renshaw Riffle Cross Section 275+55

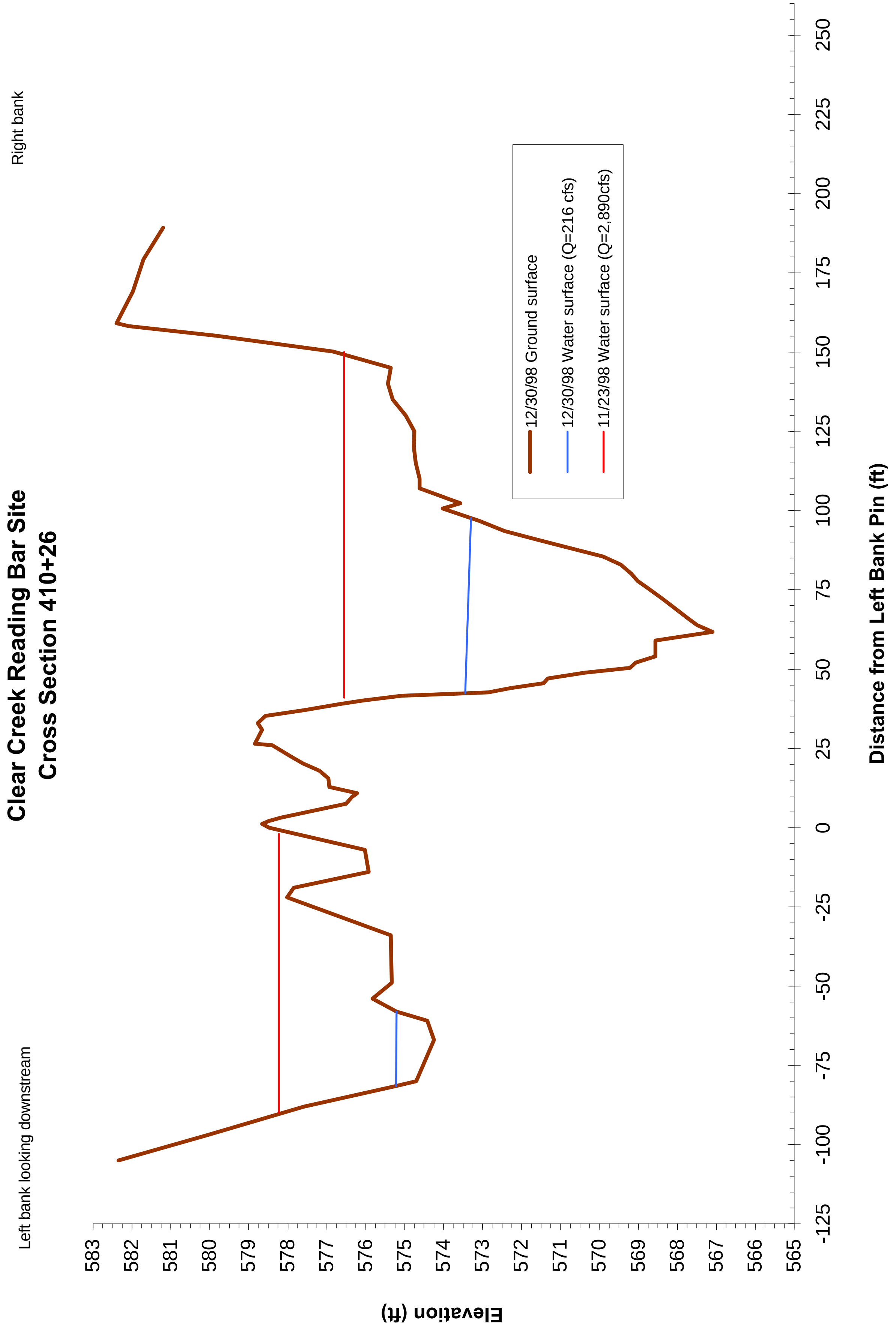


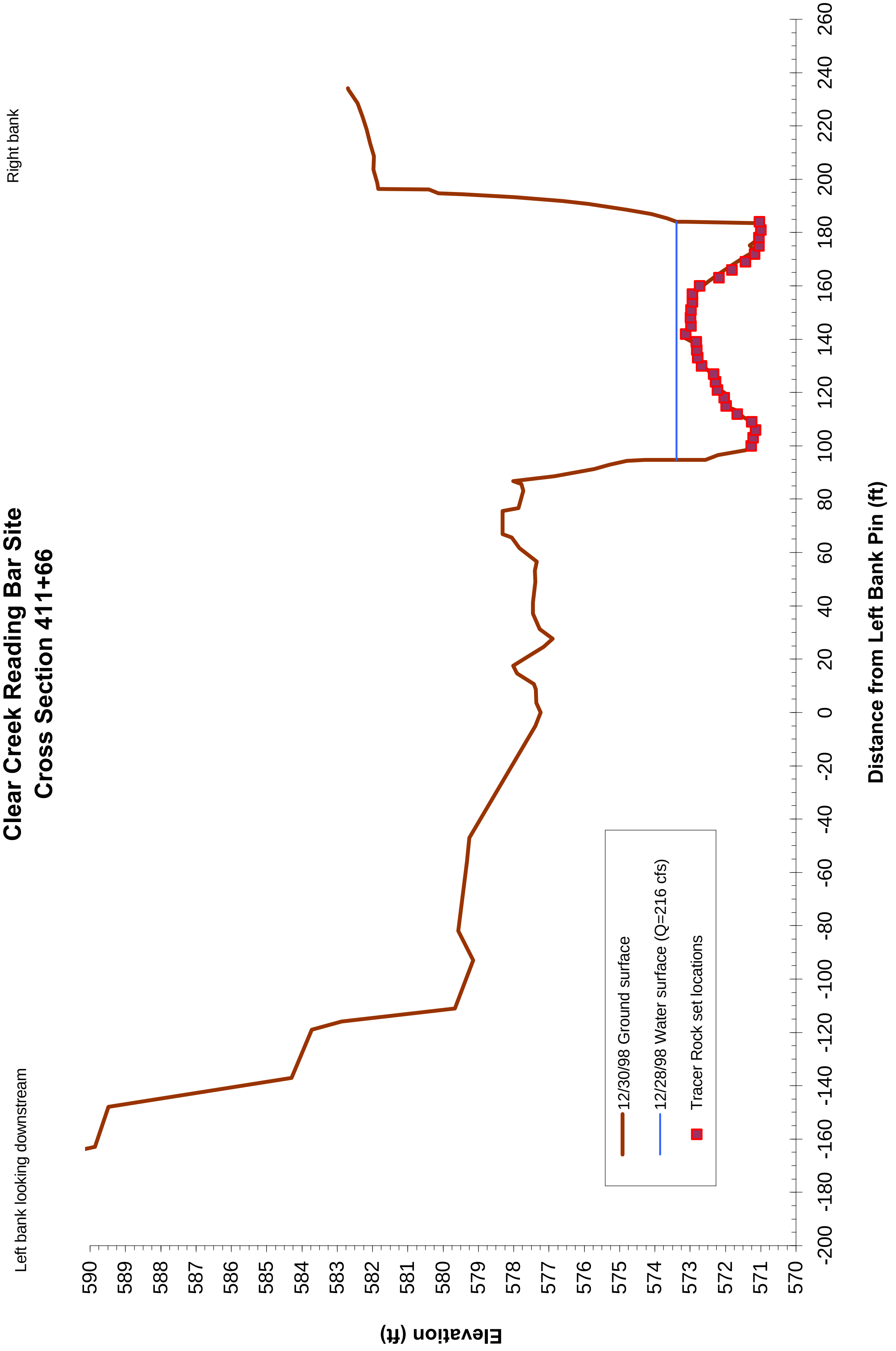
Clear Creek Renshaw Riffle Site Cross Section 277+55

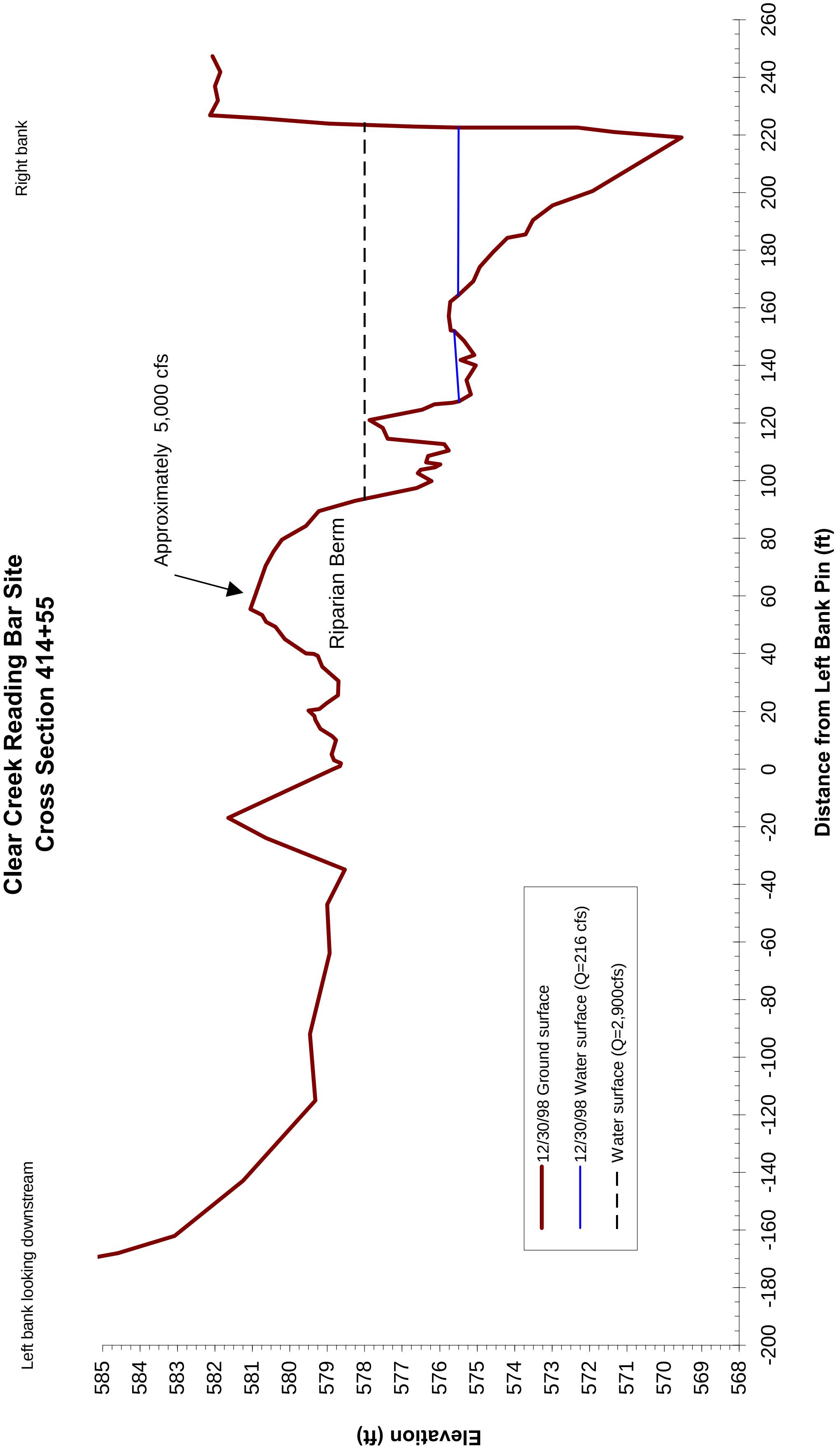


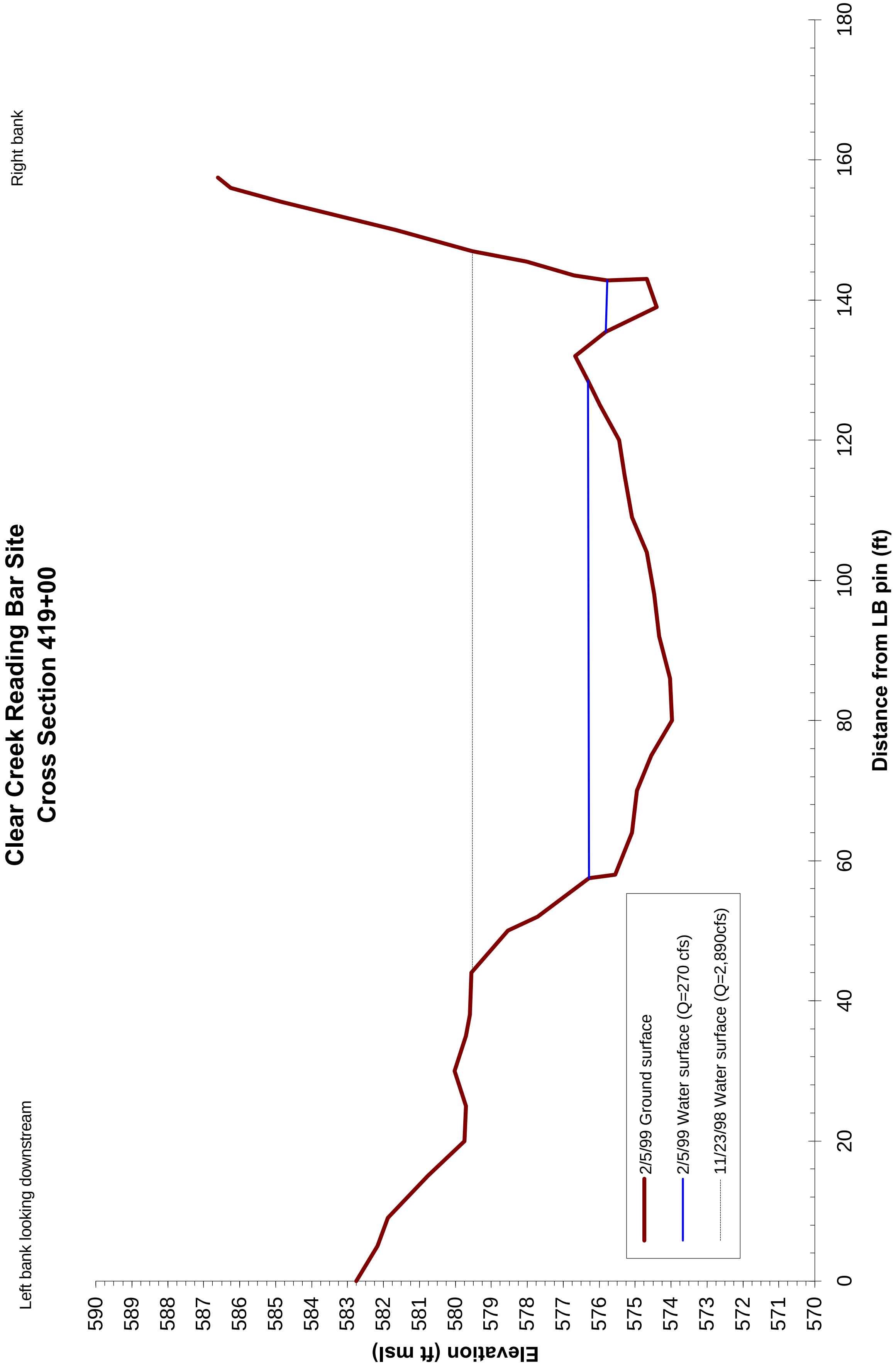
Clear Creek Renshaw Riffle Site Cross Section 280+25

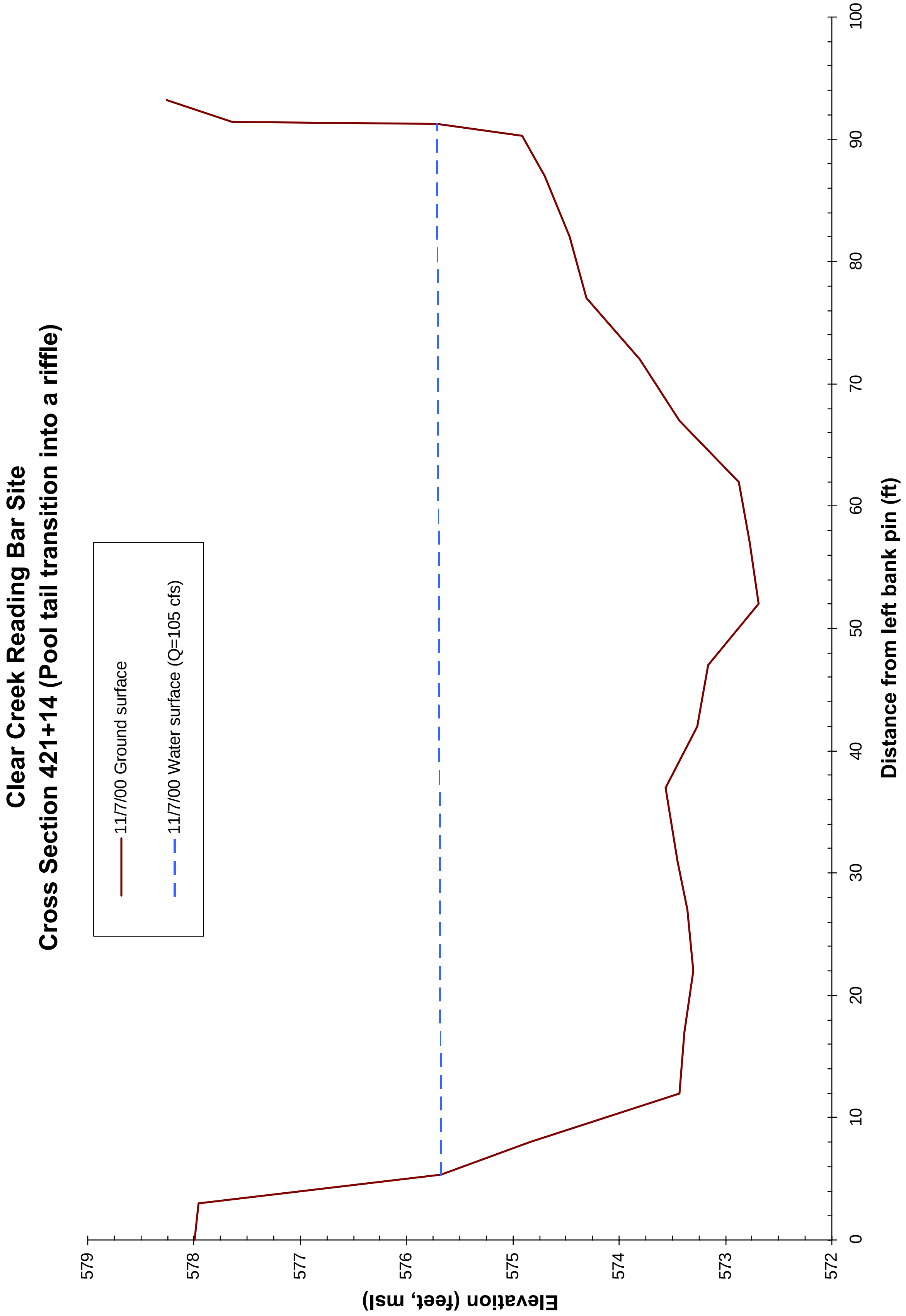

Clear Creek Renshaw Riffle Site Cross Section 283+20
Left bank looking downstream
Right bank
Elevation (ft msl)
Distance from LB pin (ft)
500
499
498
497
496
495
494
493
492
491
490
489
488
487
486
485
484
483
482
481
480
0
50
100
150
200
250
02/16/99 Ground surface
02/16/99 Water surface (Q=690 cfs)
02/12/99 Water surface (Q=333 cfs)
02/07/99 Water surface (Q=2,900 cfs)
01/01/97 Water surface (Q=15,900 cfs)

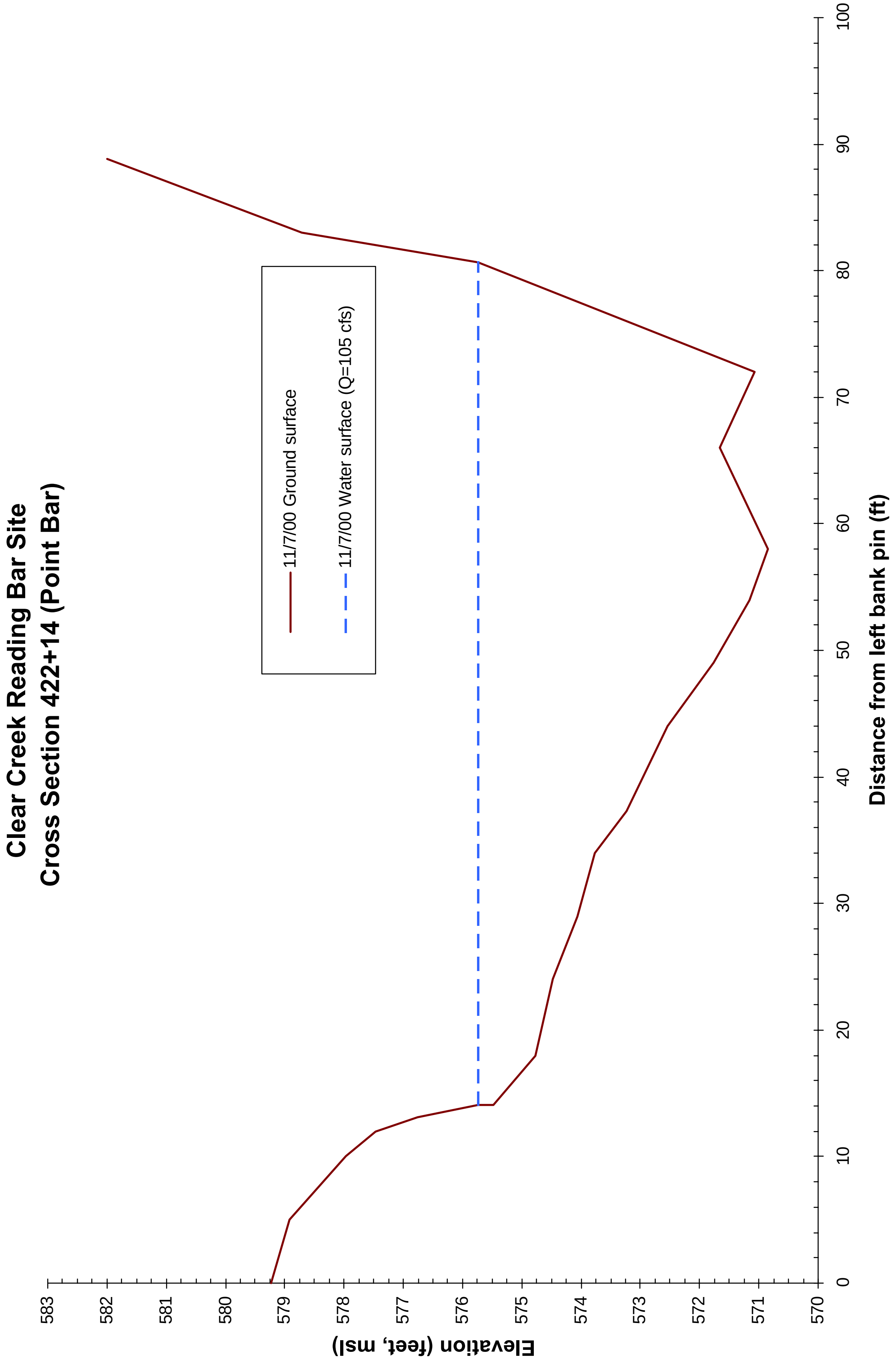

Clear Creek Reading Bar Site
Cross Section 410+26
Left bank looking downstream
Right bank
12/30/98 Ground surface
12/30/98 Water surface (Q=216 cfs)
11/23/98 Water surface (Q=2,890cfs)
Elevation (ft)
583
582
581
580
579
578
577
576
575
574
573
572
571
570
569
568
567
566
565
Distance from Left Bank Pin (ft)
-125
-100
-75
-50
-25
0
25
50
75
100
125
150
175
200
225
250


Clear Creek Reading Bar Site
Cross Section 411+66
Left bank looking downstream
Right bank
12/30/98 Ground surface
12/28/98 Water surface (Q=216 cfs)
Tracer Rock set locations
Elevation (ft)
590
589
588
587
586
585
584
583
582
581
580
579
578
577
576
575
574
573
572
571
570
Distance from Left Bank Pin (ft)
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
180
200
220
240
260

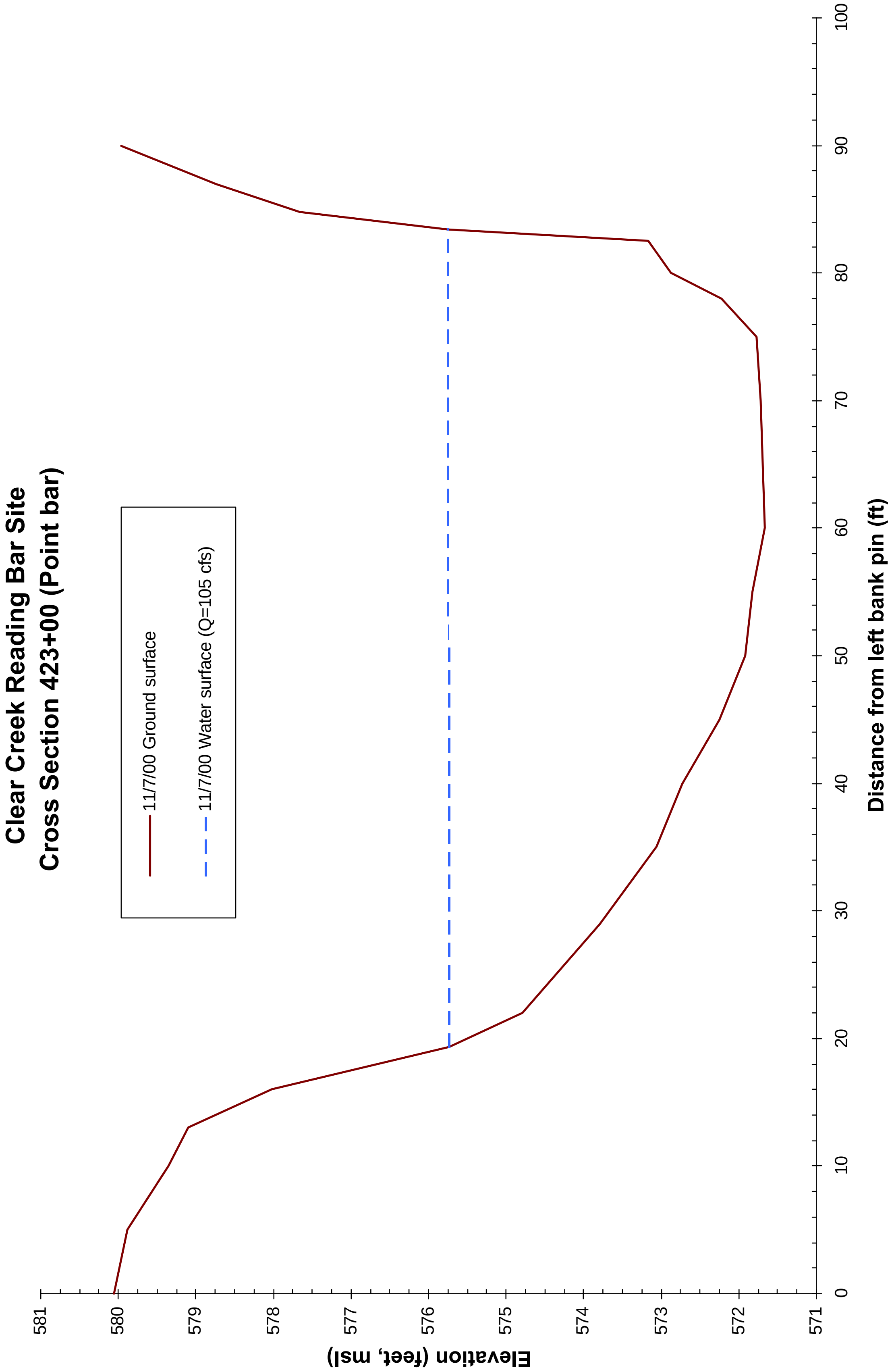

Clear Creek Reading Bar Site
Cross Section 414+55
Left bank looking downstream
Right bank
Approximately 5,000 cfs
Riparian Berm
Elevation (ft)
Distance from Left Bank Pin (ft)
585
584
583
582
581
580
579
578
577
576
575
574
573
572
571
570
569
568
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
180
200
220
240
260
12/30/98 Ground surface
12/30/98 Water surface (Q=216 cfs)
Water surface (Q=2,900cfs)


Clear Creek Reading Bar Site
Cross Section 419+00
Left bank looking downstream
Right bank
Elevation (ft msl)
590
589
588
587
586
585
584
583
582
581
580
579
578
577
576
575
574
573
572
571
570
Distance from LB pin (ft)
0
20
40
60
80
100
120
140
160
180
2/5/99 Ground surface
2/5/99 Water surface (Q=270 cfs)
11/23/98 Water surface (Q=2,890cfs)

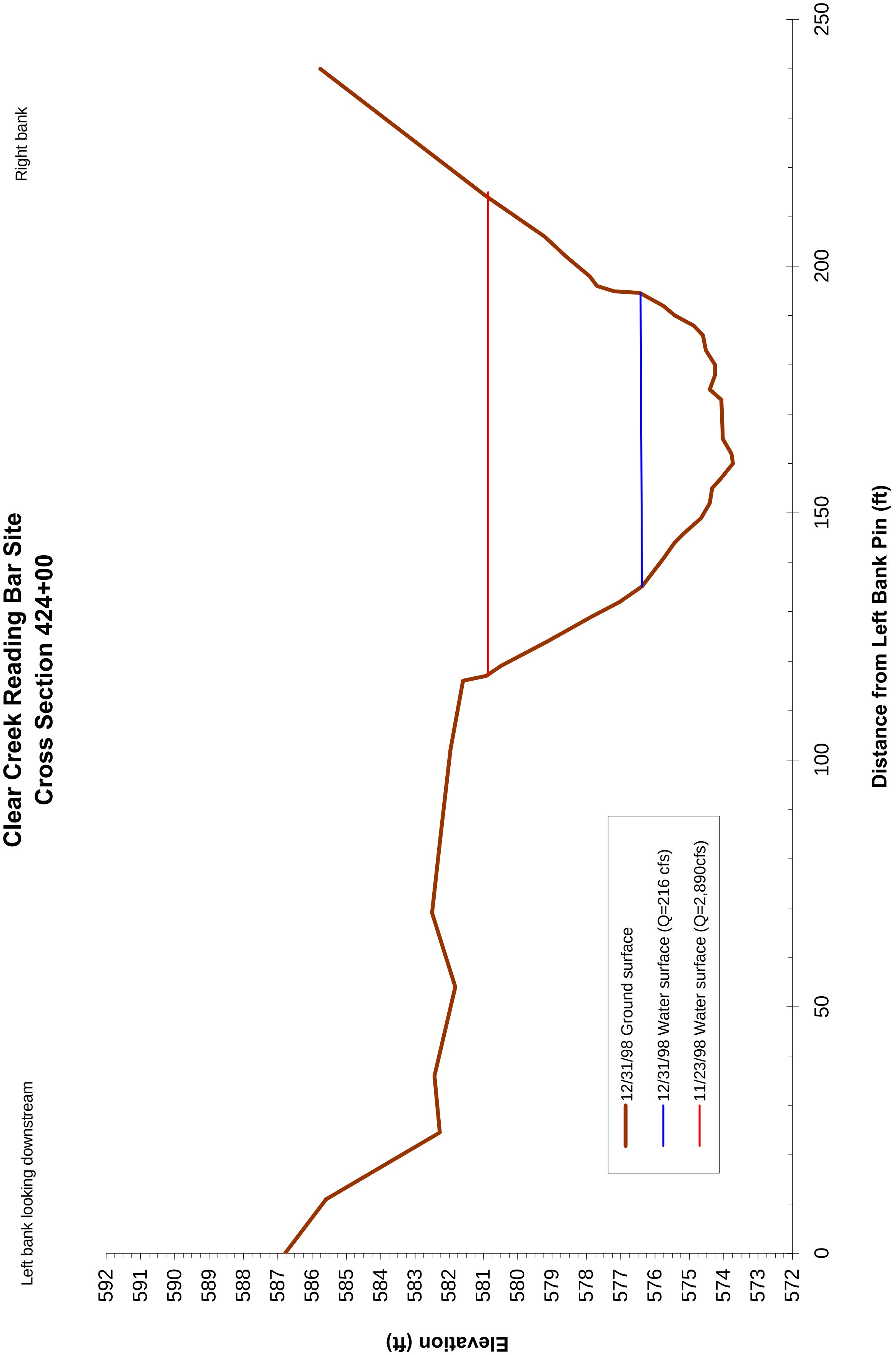

Clear Creek Reading Bar Site
Cross Section 421+14 (Pool tail transition into a riffle)
11/7/00 Ground surface
11/7/00 Water surface (Q=105 cfs)
Elevation (feet, msl)
579
578
577
576
575
574
573
572
Distance from left bank pin (ft)
0
10
20
30
40
50
60
70
80
90
100

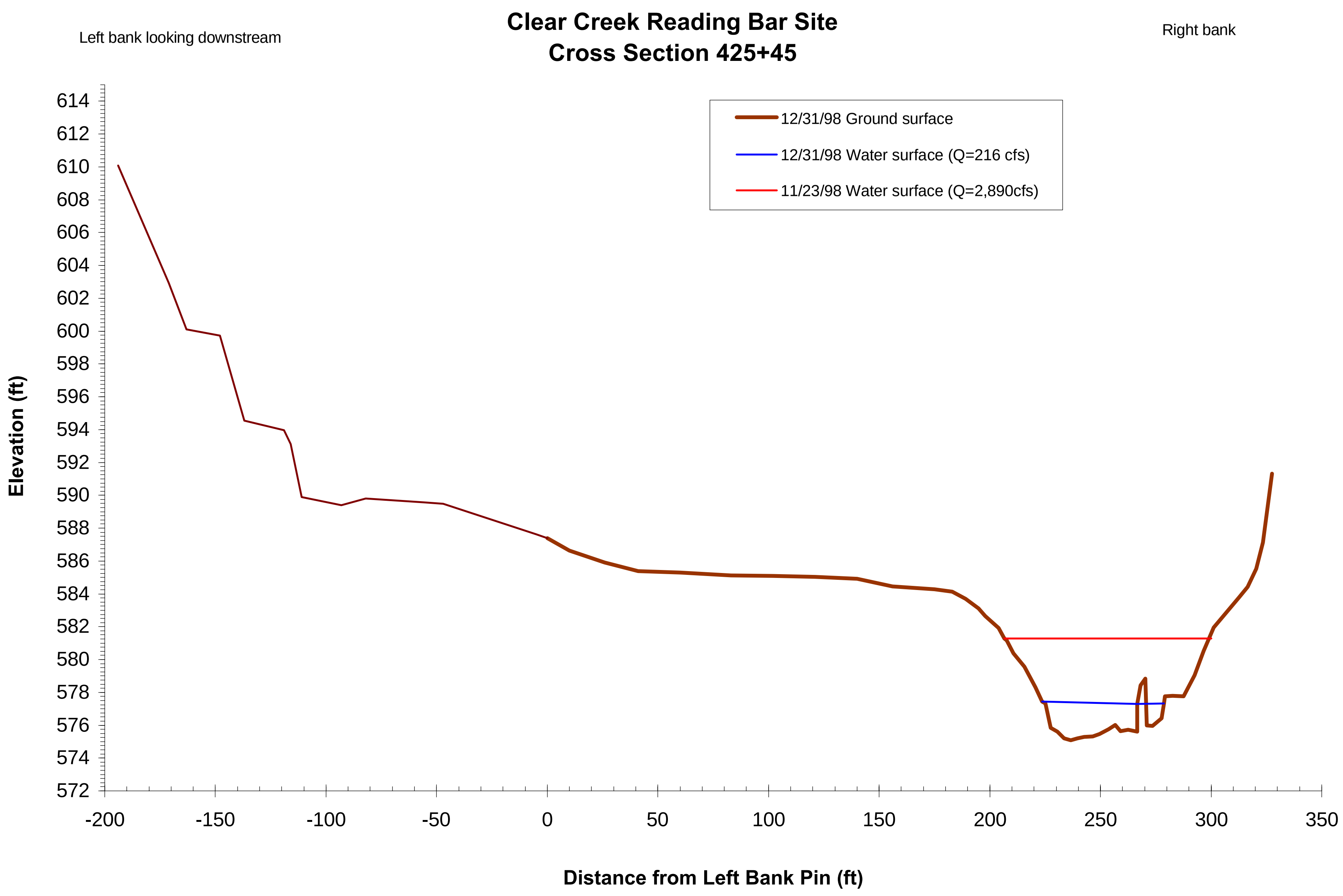


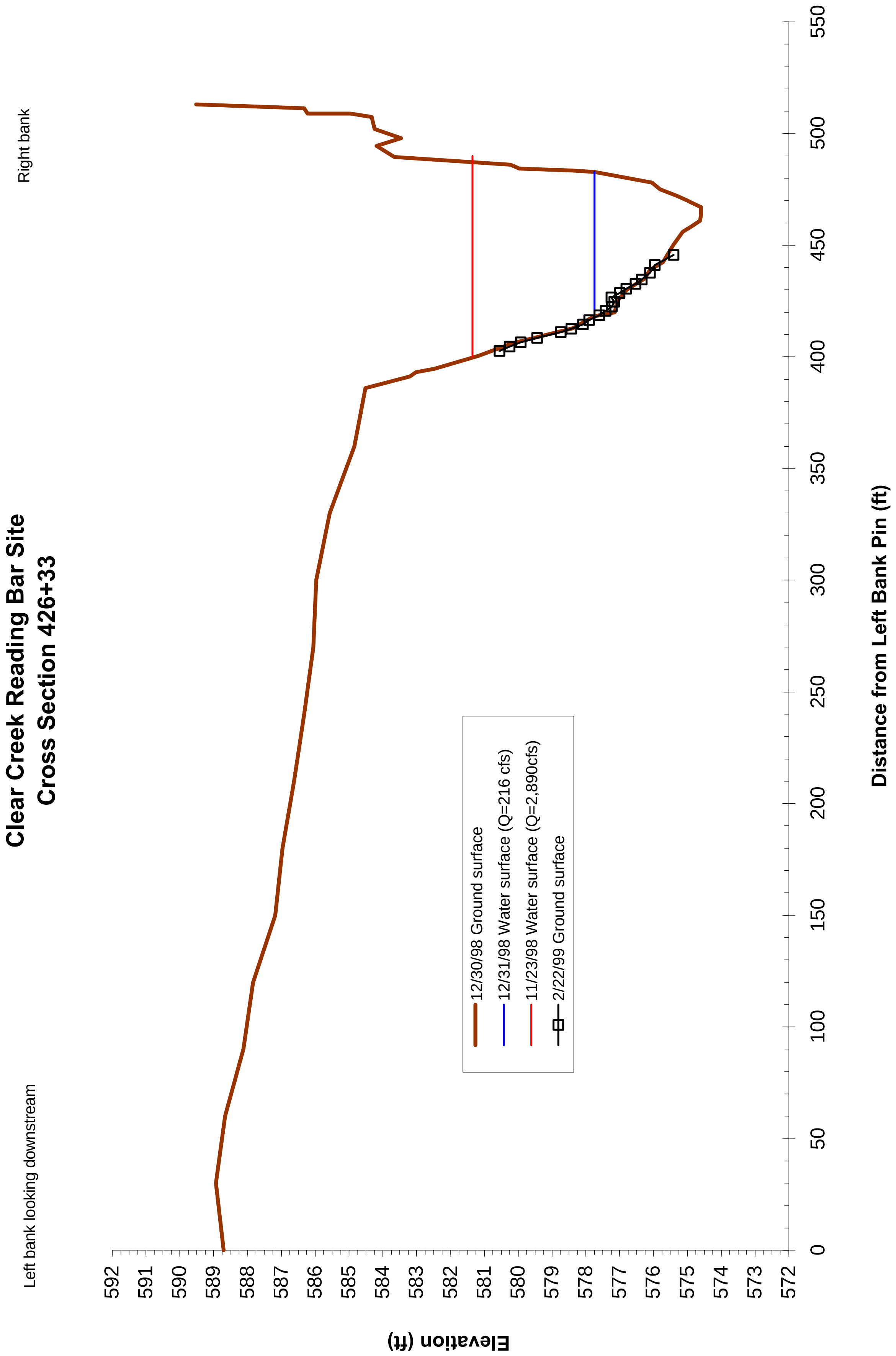
Clear Creek Reading Bar Site
Cross Section 422+14 (Point Bar)

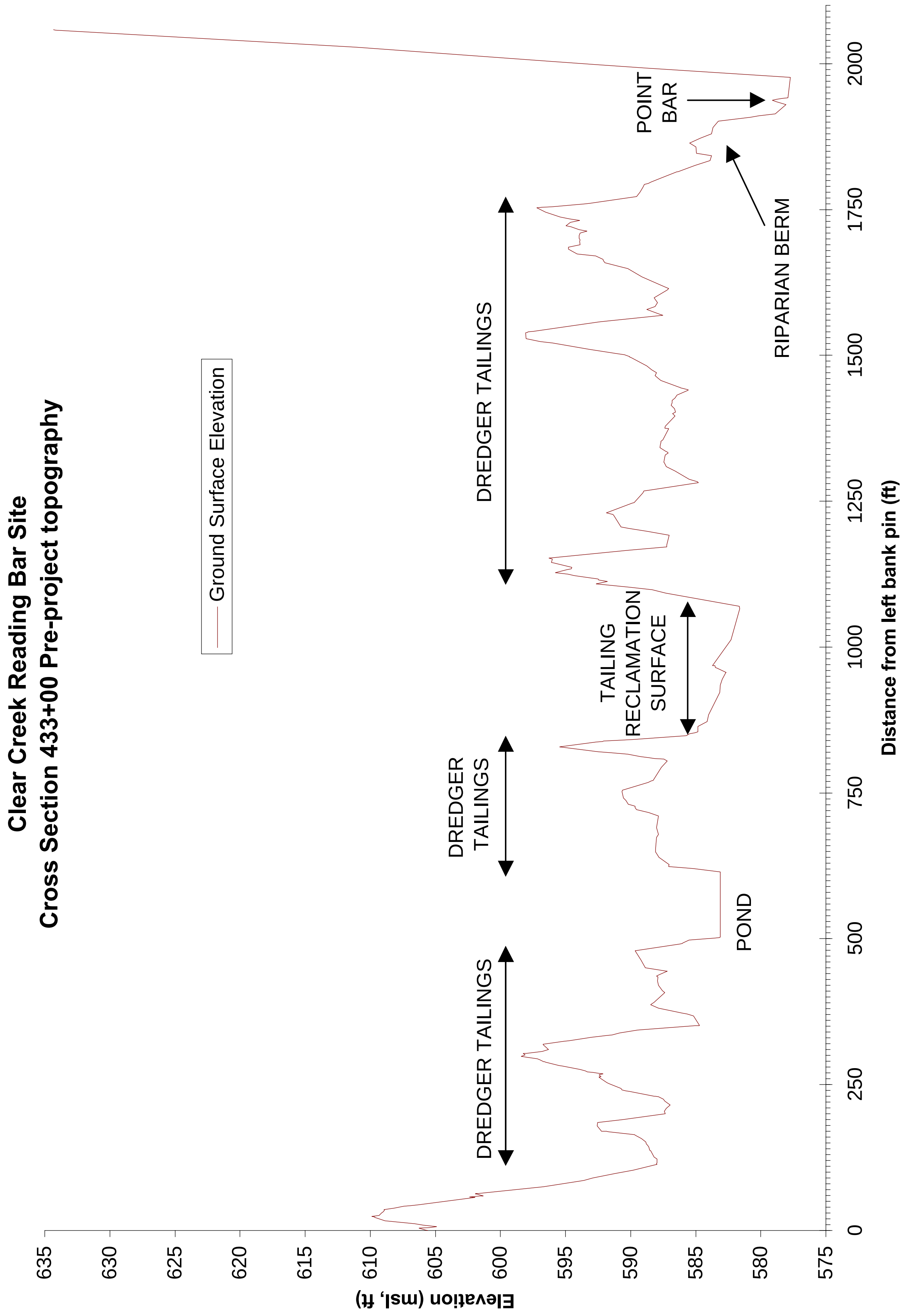


Clear Creek Reading Bar Site
Cross Section 423+00 (Point bar)

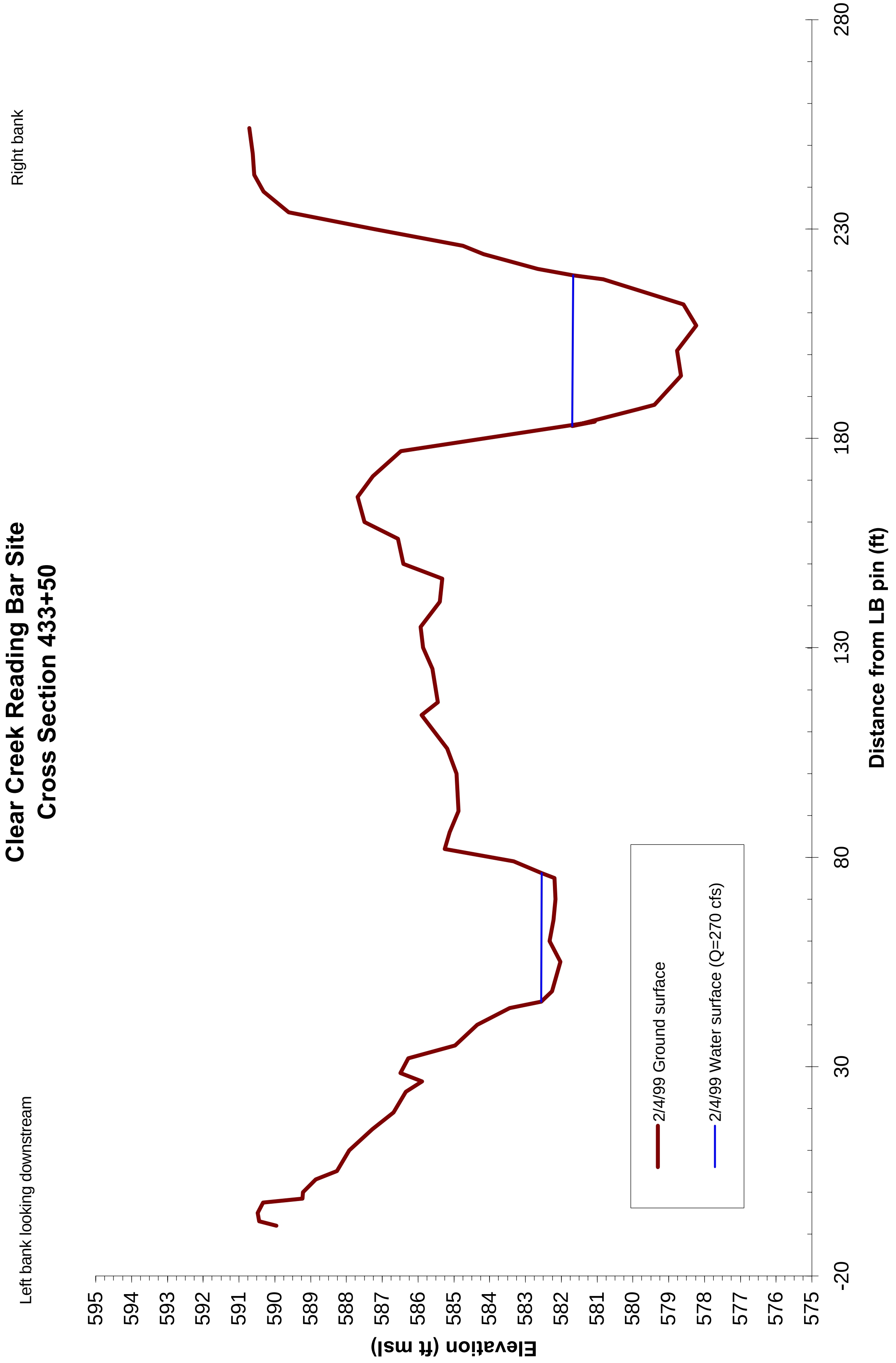

Clear Creek Reading Bar Site
Cross Section 424+00
Left bank looking downstream
Right bank
12/31/98 Ground surface
12/31/98 Water surface (Q=216 cfs)
11/23/98 Water surface (Q=2,890cfs)
Elevation (ft)
592
591
590
589
588
587
586
585
584
583
582
581
580
579
578
577
576
575
574
573
572
Distance from Left Bank Pin (ft)
0
50
100
150
200
250

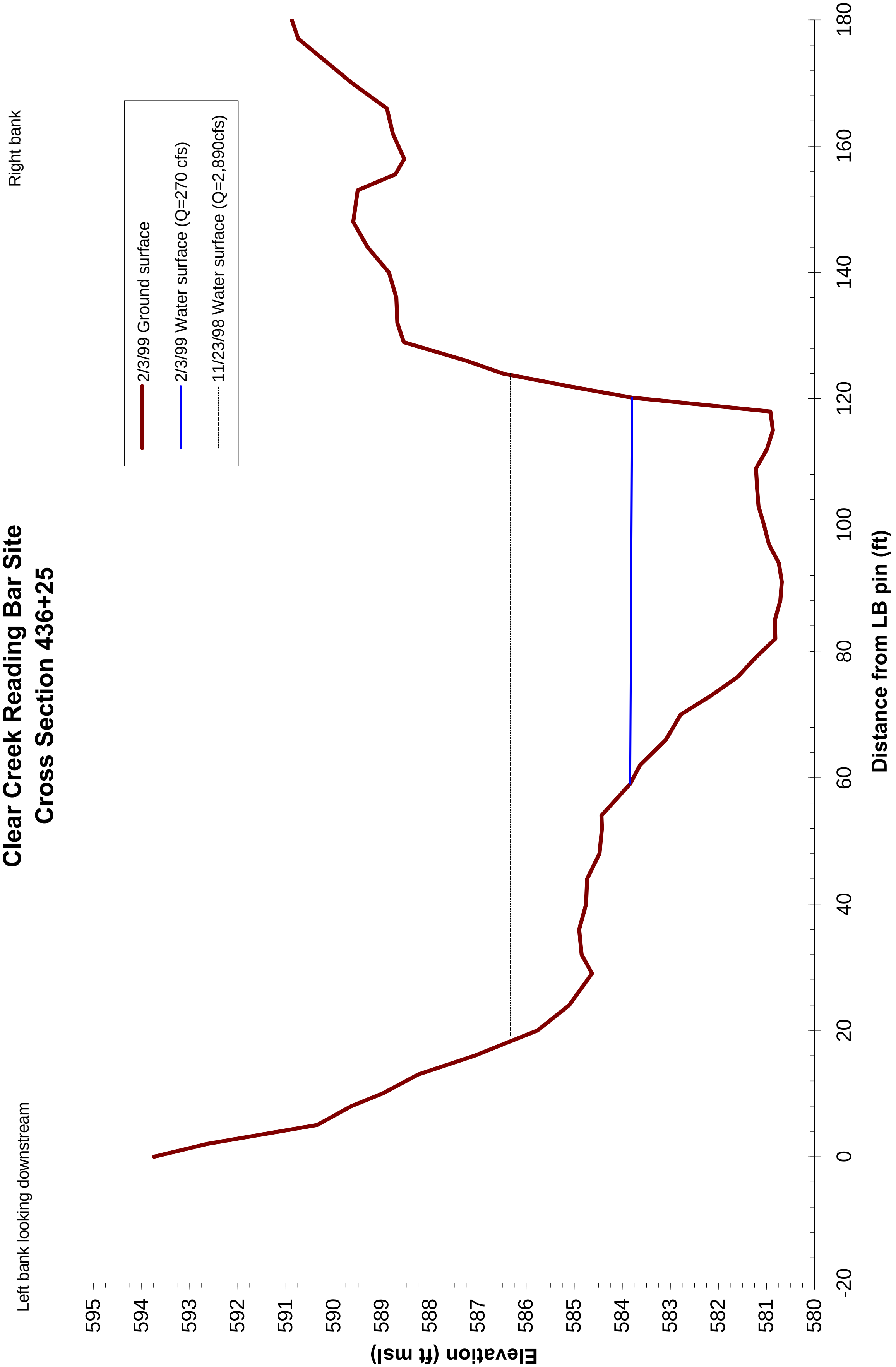

Clear Creek Reading Bar Site
Cross Section 425+45
Left bank looking downstream
Right bank
12/31/98 Ground surface
12/31/98 Water surface (Q=216 cfs)
11/23/98 Water surface (Q=2,890cfs)
Elevation (ft)
614
612
610
608
606
604
602
600
598
596
594
592
590
588
586
584
582
580
578
576
574
572
-200
-150
-100
-50
0
50
100
150
200
250
300
350
Distance from Left Bank Pin (ft)


Clear Creek Reading Bar Site
Cross Section 426+33
Left bank looking downstream
Right bank
Elevation (ft)
592
591
590
589
588
587
586
585
584
583
582
581
580
579
578
577
576
575
574
573
572
Distance from Left Bank Pin (ft)
0
50
100
150
200
250
300
350
400
450
500
550
12/30/98 Ground surface
12/31/98 Water surface (Q=216 cfs)
11/23/98 Water surface (Q=2,890cfs)
2/22/99 Ground surface

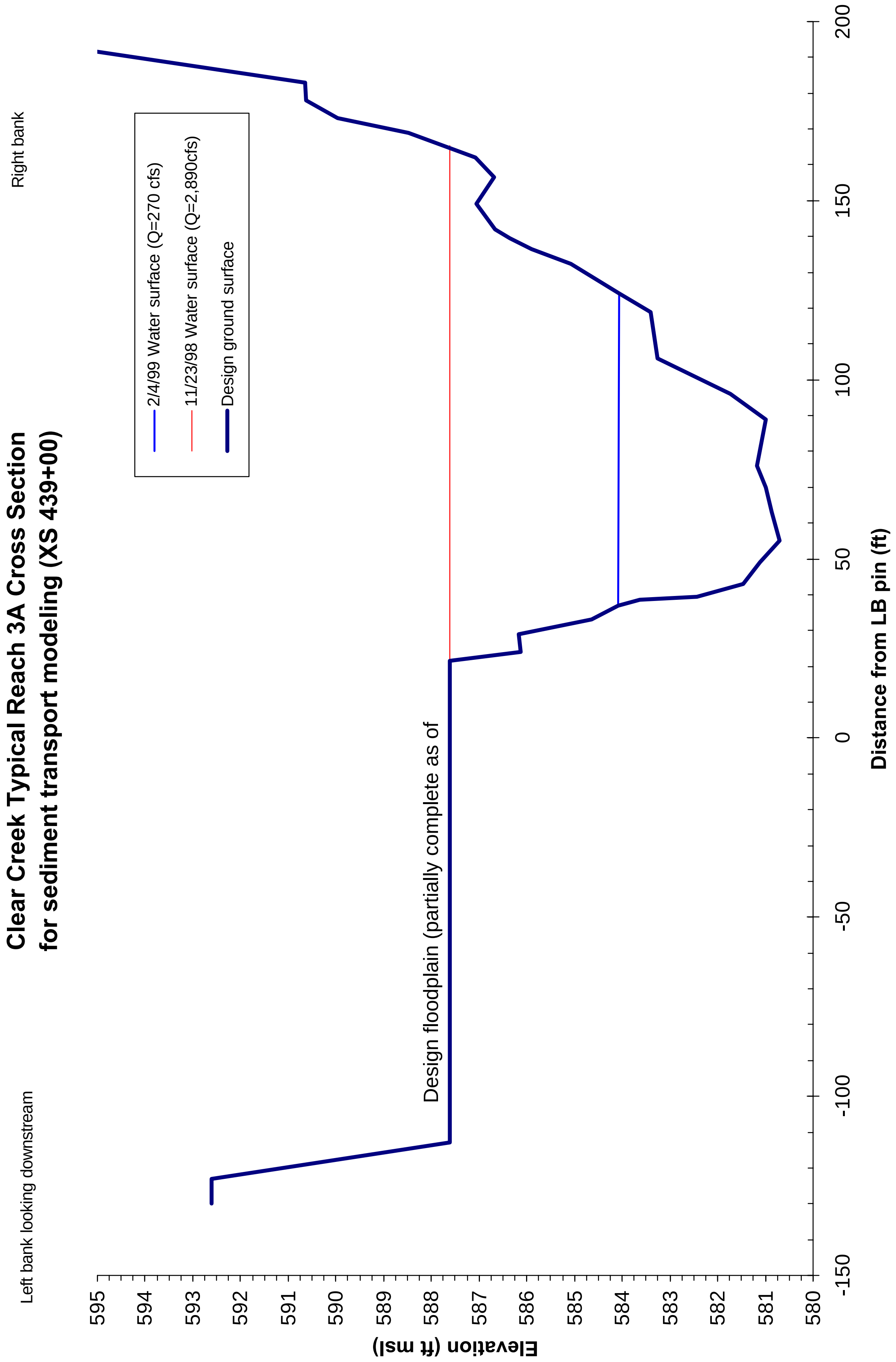


Clear Creek Reading Bar Site
Cross Section 433+00 Pre-project topography

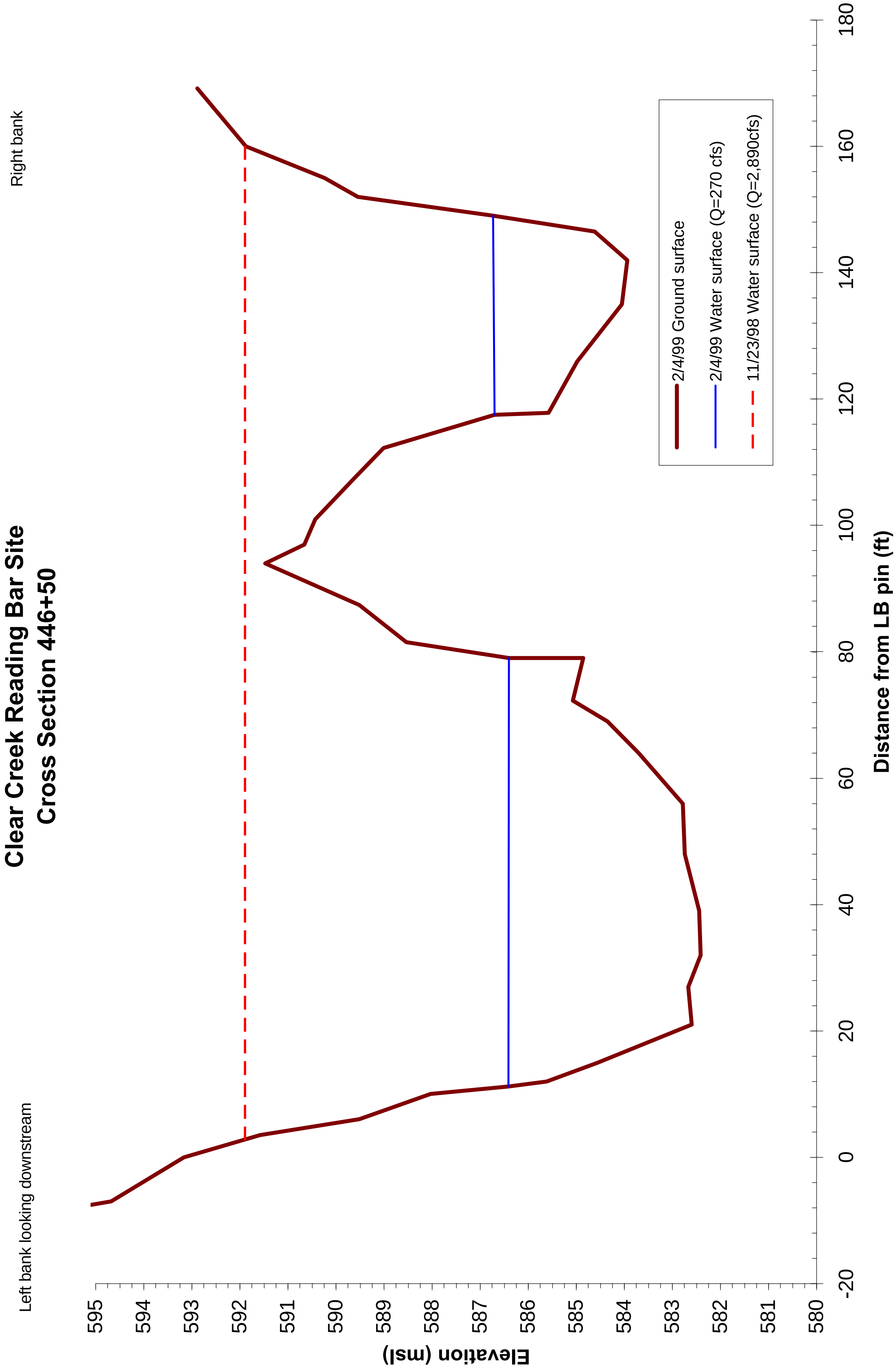

Clear Creek Reading Bar Site
Cross Section 433+50
Left bank looking downstream
Right bank
Elevation (ft msl)
595
594
593
592
591
590
589
588
587
586
585
584
583
582
581
580
579
578
577
576
575
Distance from LB pin (ft)
-20
30
80
130
180
230
280
2/4/99 Ground surface
2/4/99 Water surface (Q=270 cfs)

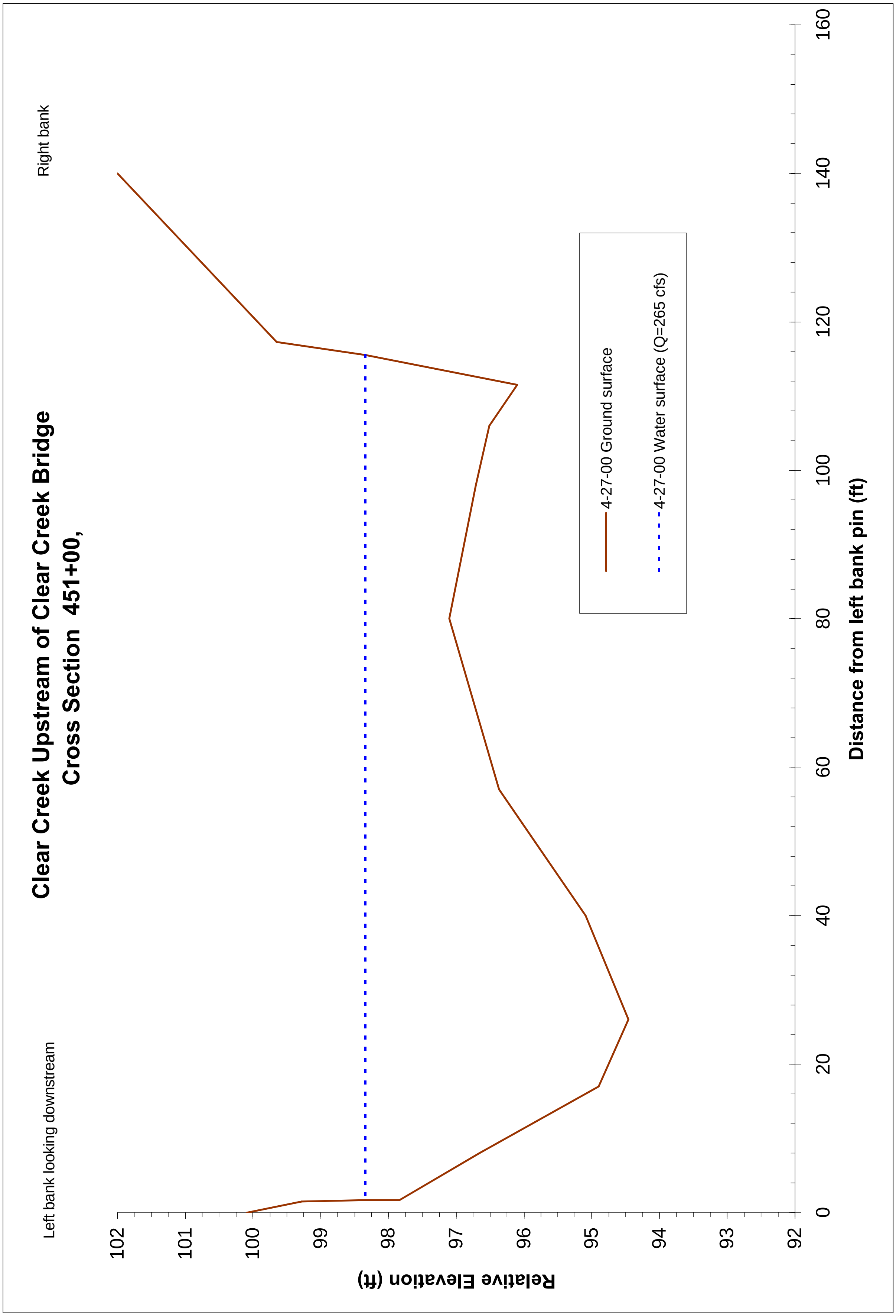


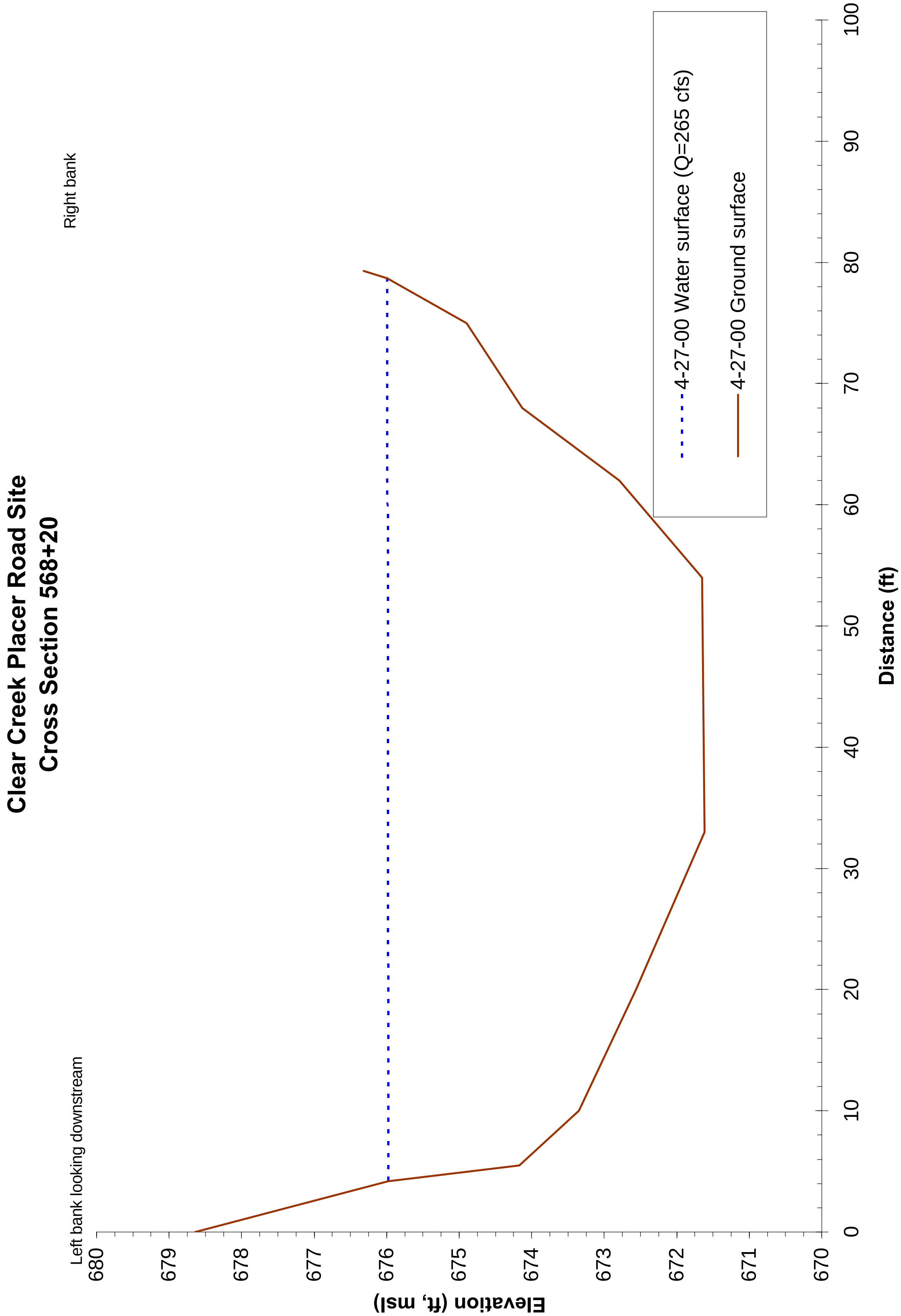
Clear Creek Reading Bar Site
Cross Section 436+25

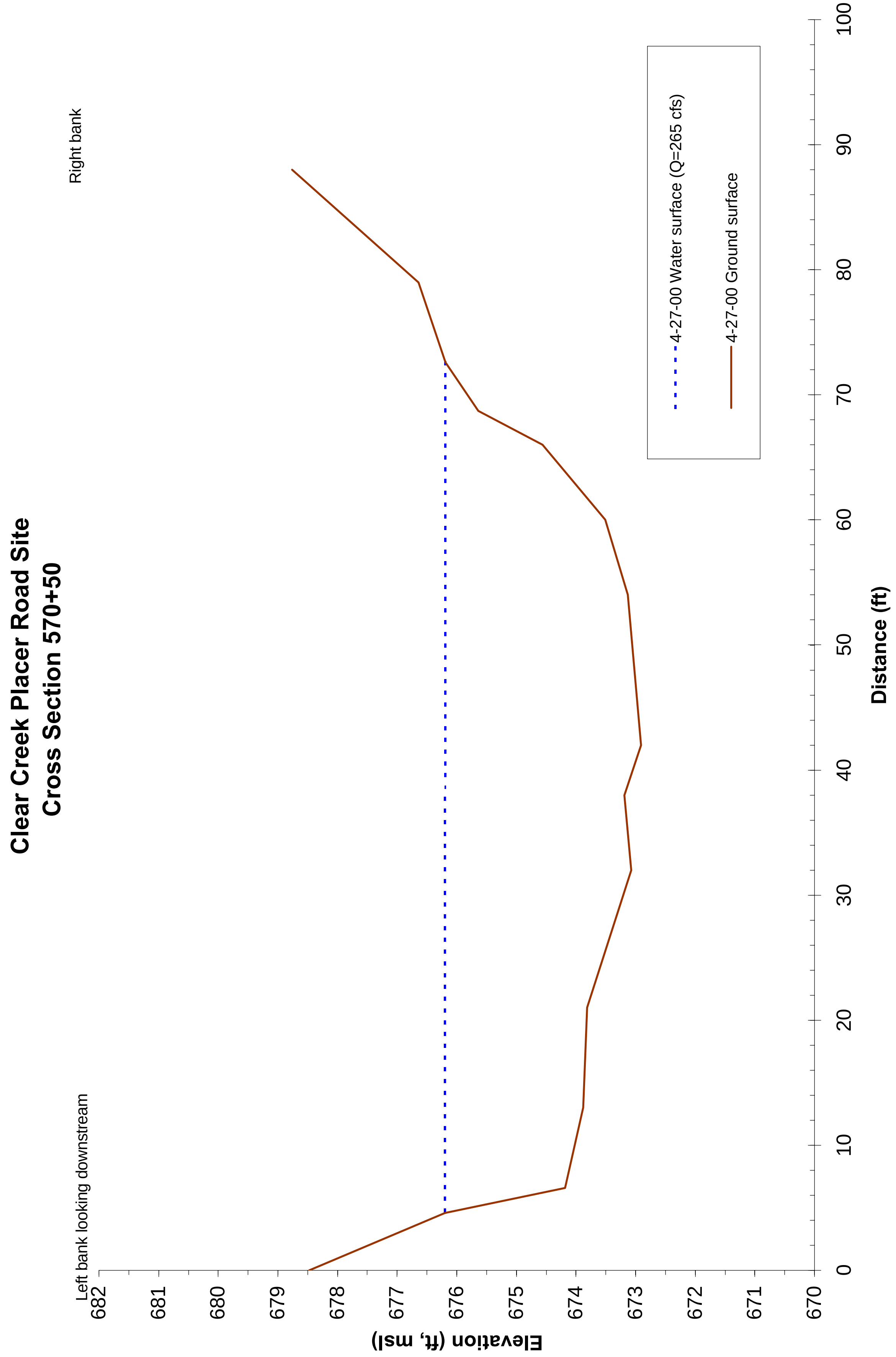


Clear Creek Typical Reach 3A Cross Section for sediment transport modeling (XS 439+00)

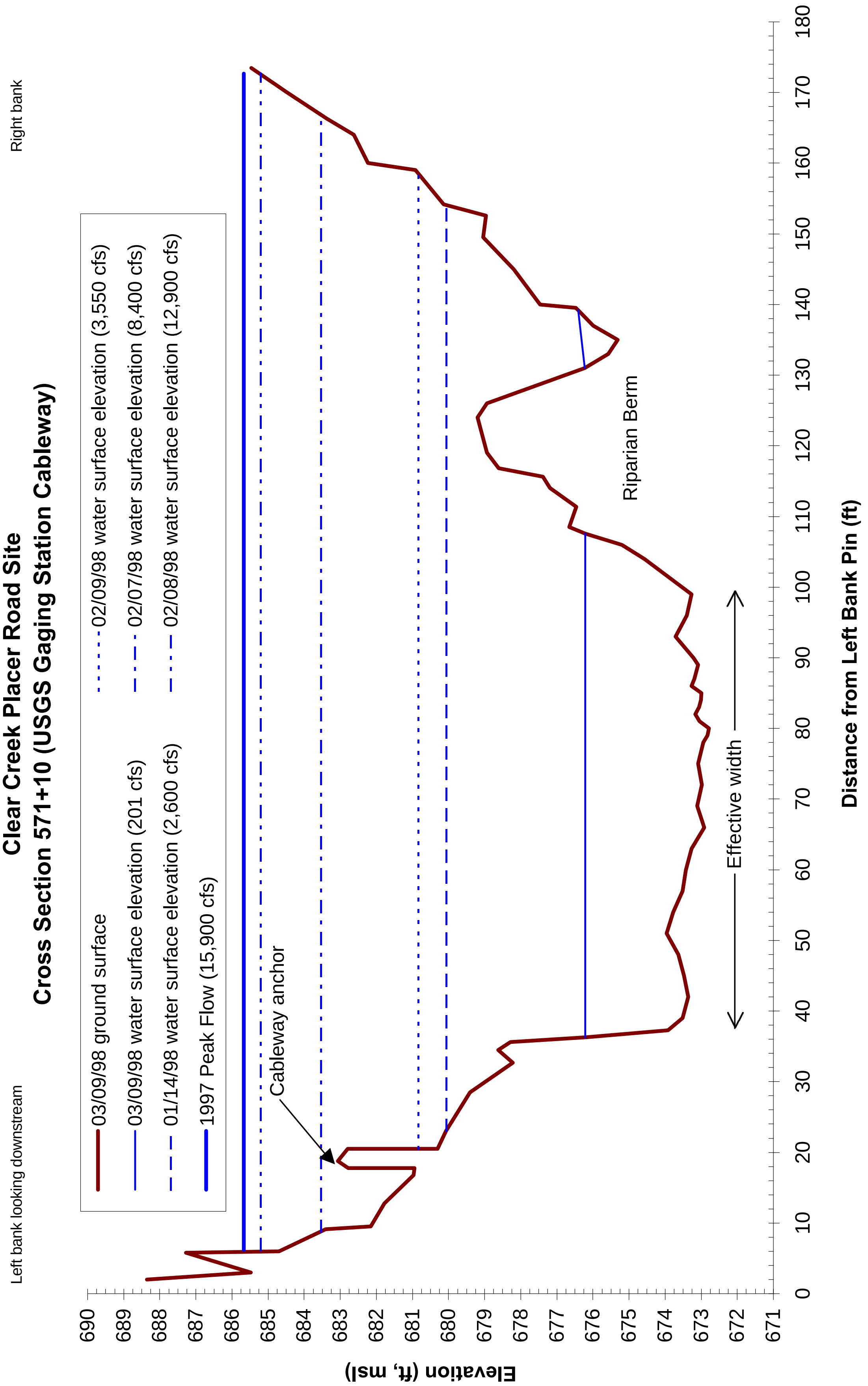

Clear Creek Reading Bar Site
Cross Section 446+50
Left bank looking downstream
Right bank
2/4/99 Ground surface
2/4/99 Water surface (Q=270 cfs)
11/23/98 Water surface (Q=2,890cfs)
Elevation (msl)
595
594
593
592
591
590
589
588
587
586
585
584
583
582
581
580
Distance from LB pin (ft)
-20
0
20
40
60
80
100
120
140
160
180

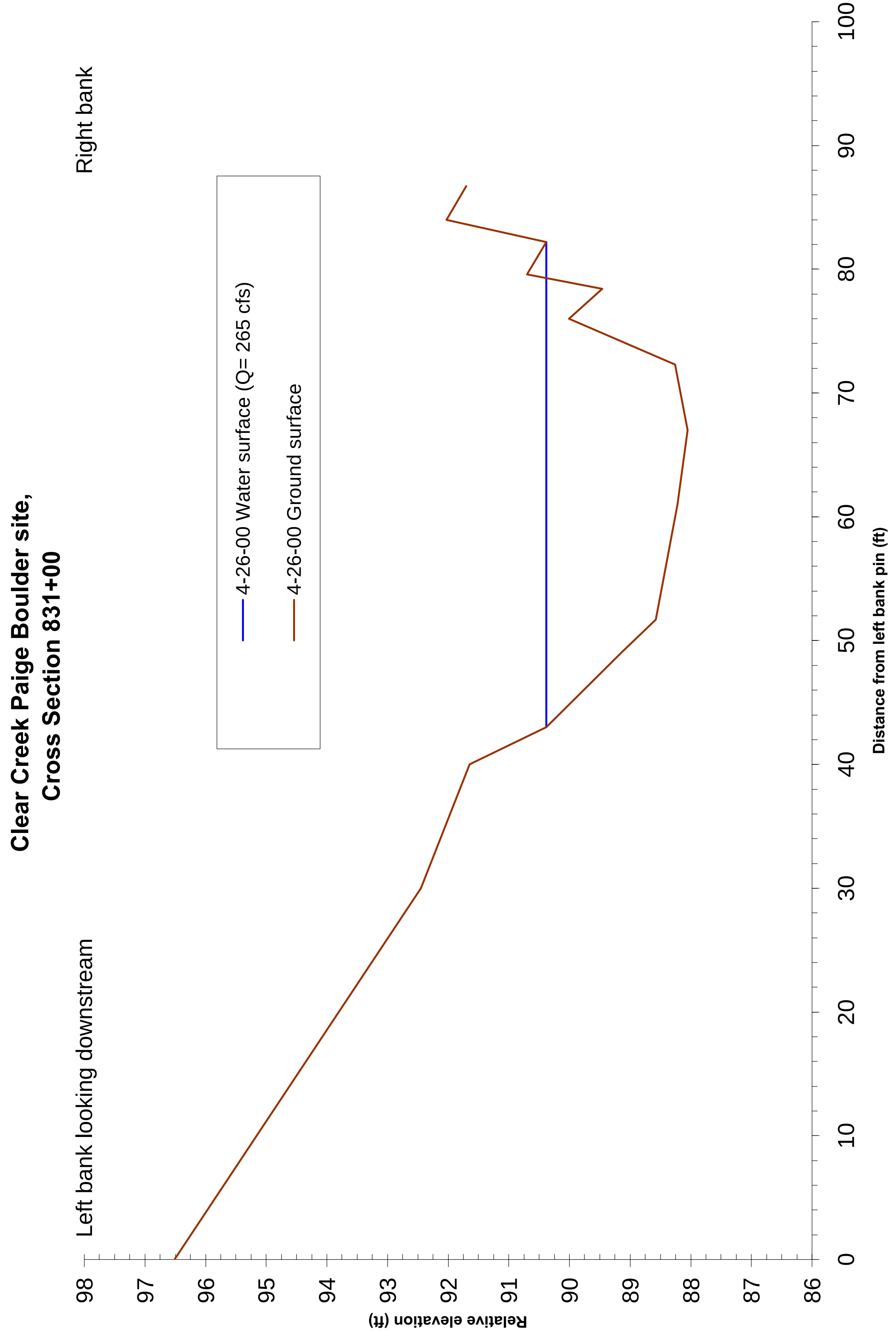

Clear Creek Upstream of Clear Creek Bridge
Cross Section 451+00,

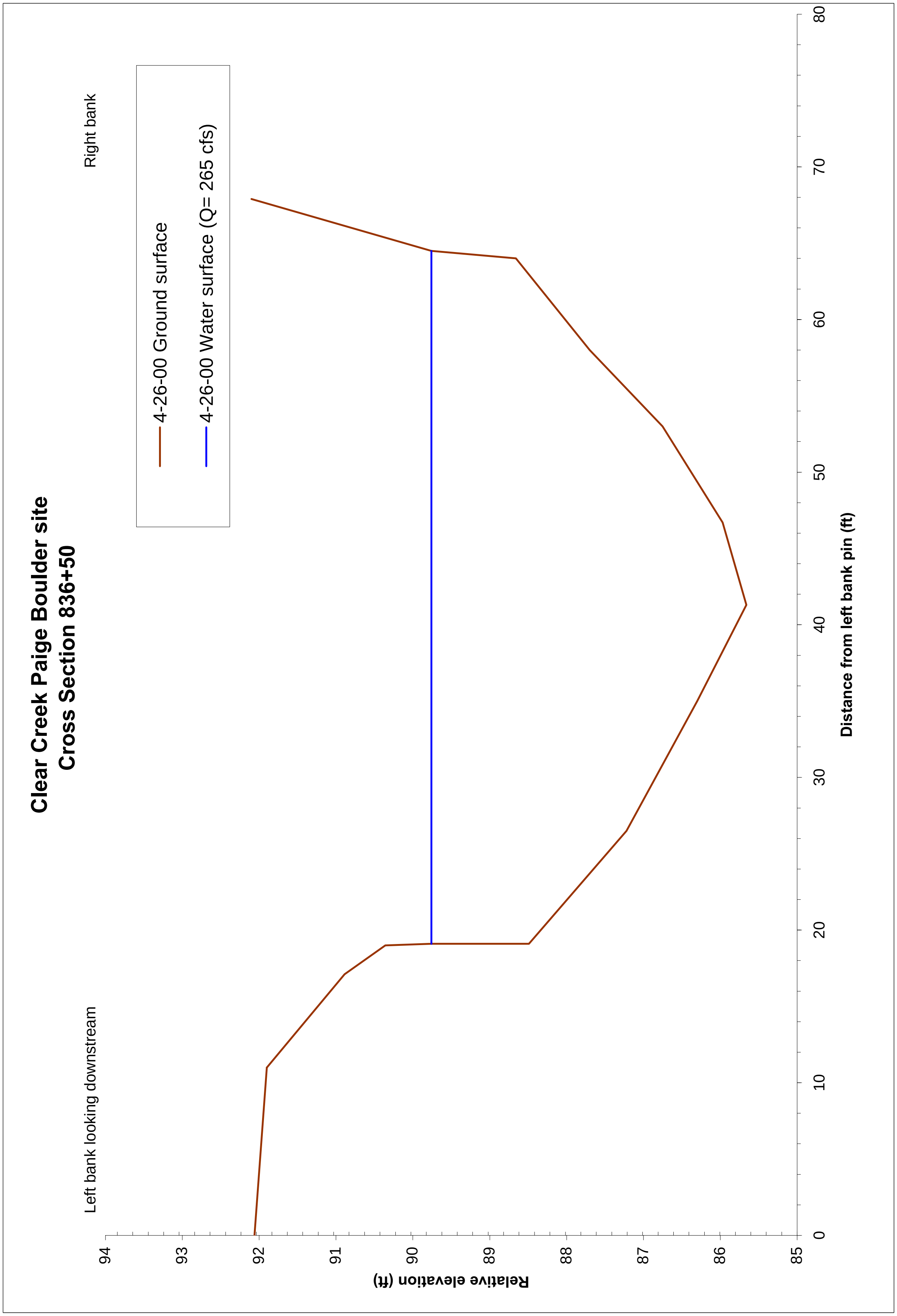

Clear Creek Placer Road Site
Cross Section 568+20
Left bank looking downstream
Right bank
4-27-00 Water surface (Q=265 cfs)
4-27-00 Ground surface
Elevation (ft, msl)
680
679
678
677
676
675
674
673
672
671
670
Distance (ft)
0
10
20
30
40
50
60
70
80
90
100

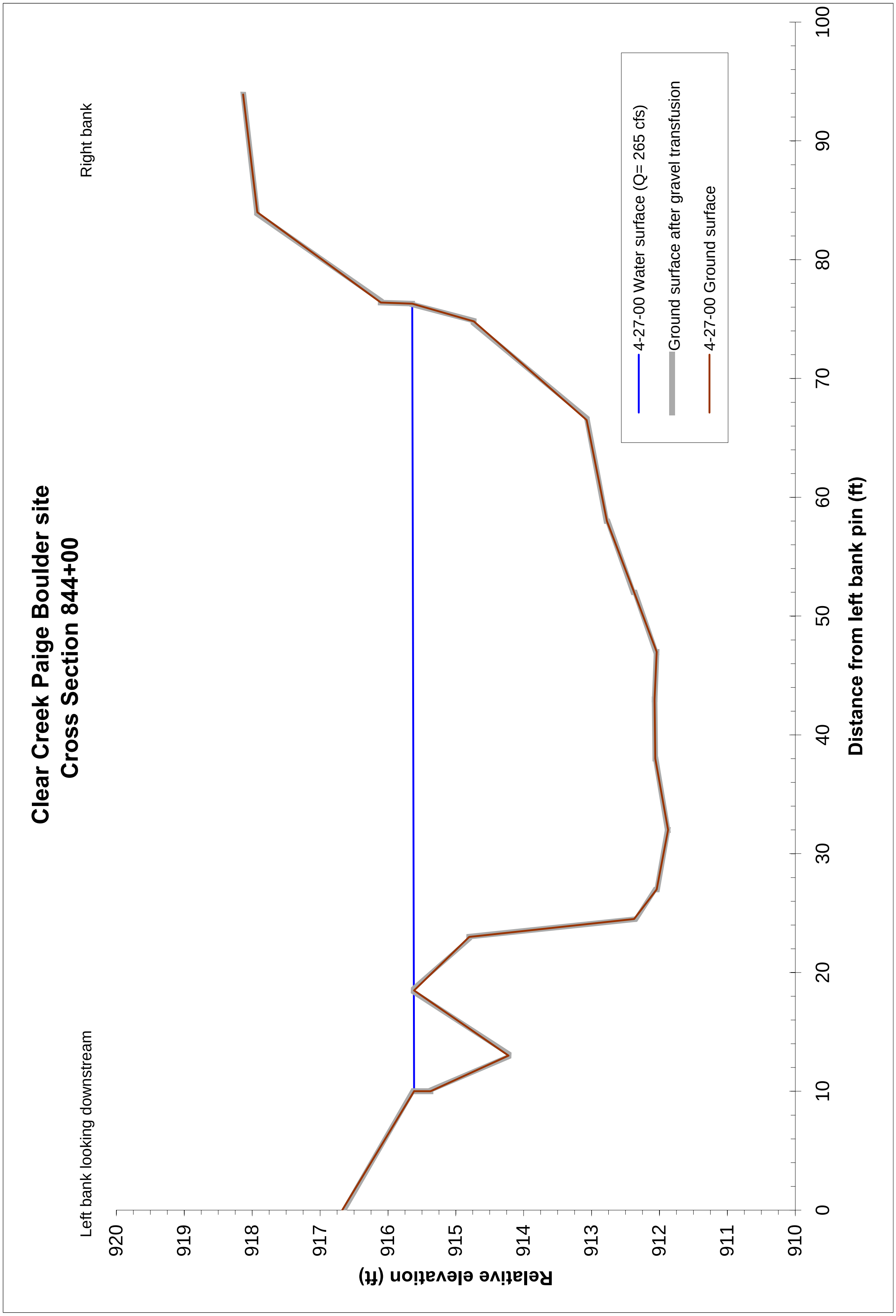


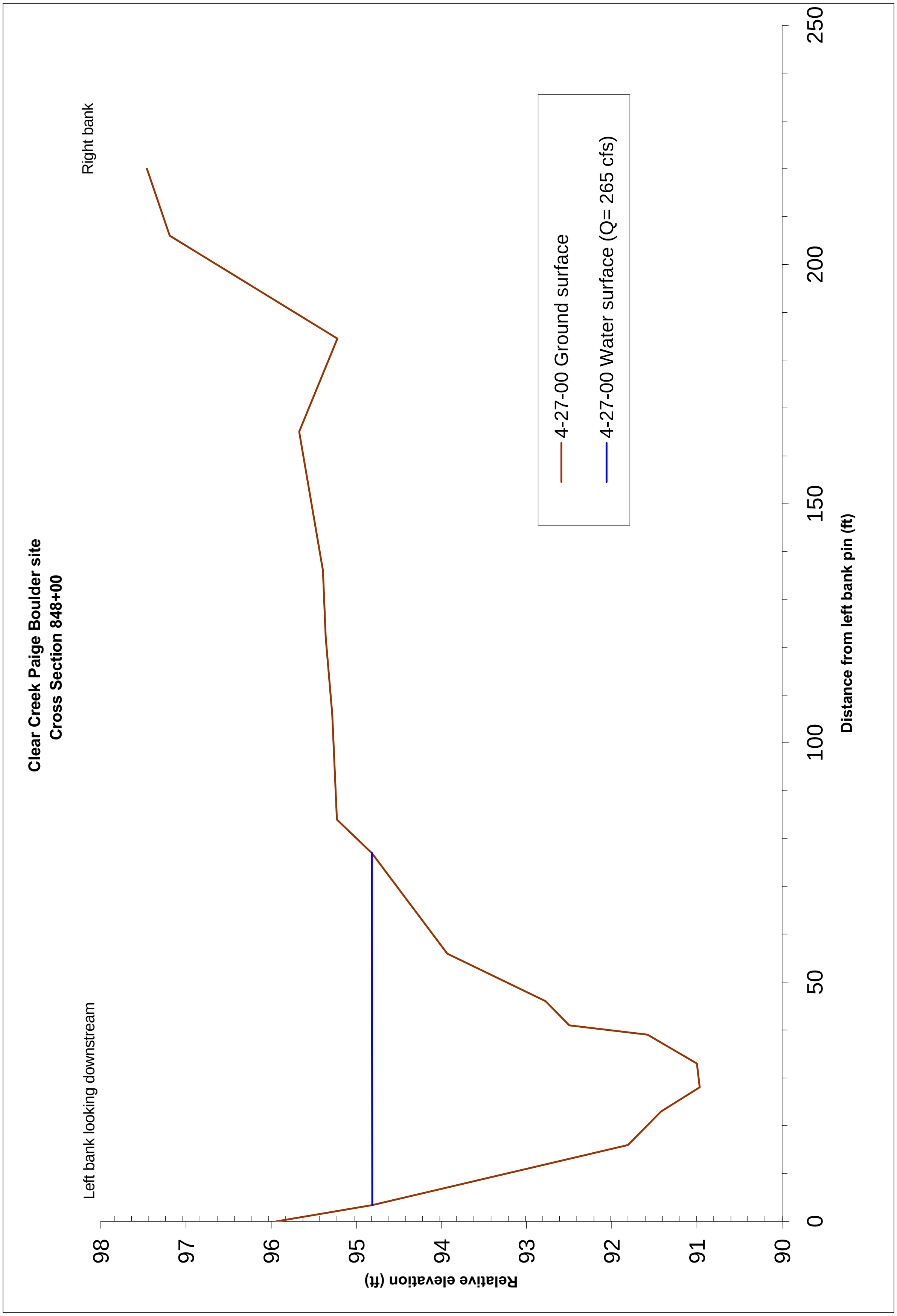
Clear Creek Placer Road Site
Cross Section 570+50

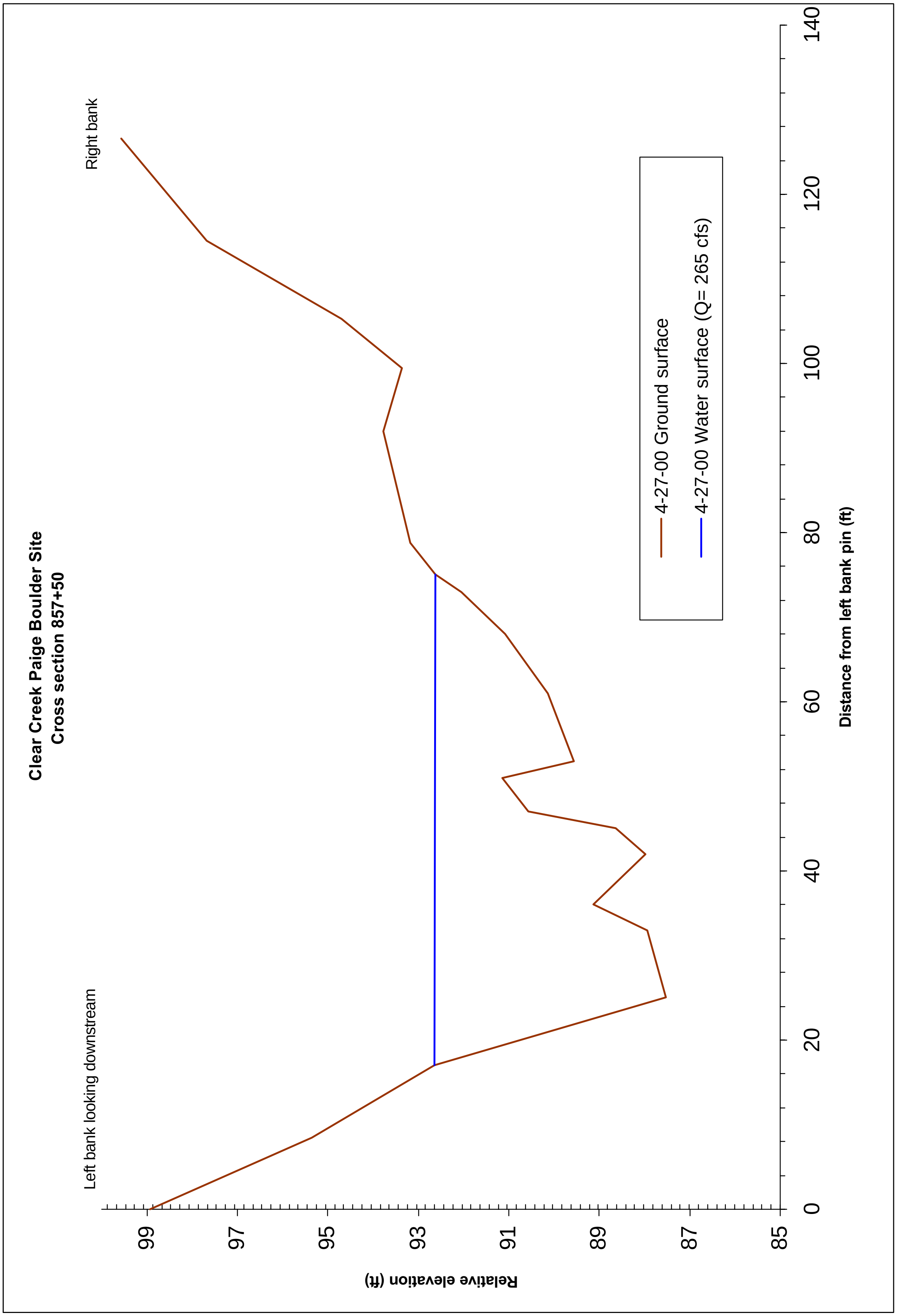

Clear Creek Placer Road Site
Cross Section 571+10 (USGS Gaging Station Cableway)
Left bank looking downstream
Right bank
03/09/98 ground surface
03/09/98 water surface elevation (201 cfs)
01/14/98 water surface elevation (2,600 cfs)
1997 Peak Flow (15,900 cfs)
02/09/98 water surface elevation (3,550 cfs)
02/07/98 water surface elevation (8,400 cfs)
02/08/98 water surface elevation (12,900 cfs)
Cableway anchor
Riparian Berm
Effective width
Elevation (ft, msl)
690
689
688
687
686
685
684
683
682
681
680
679
678
677
676
675
674
673
672
671
Distance from Left Bank Pin (ft)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180

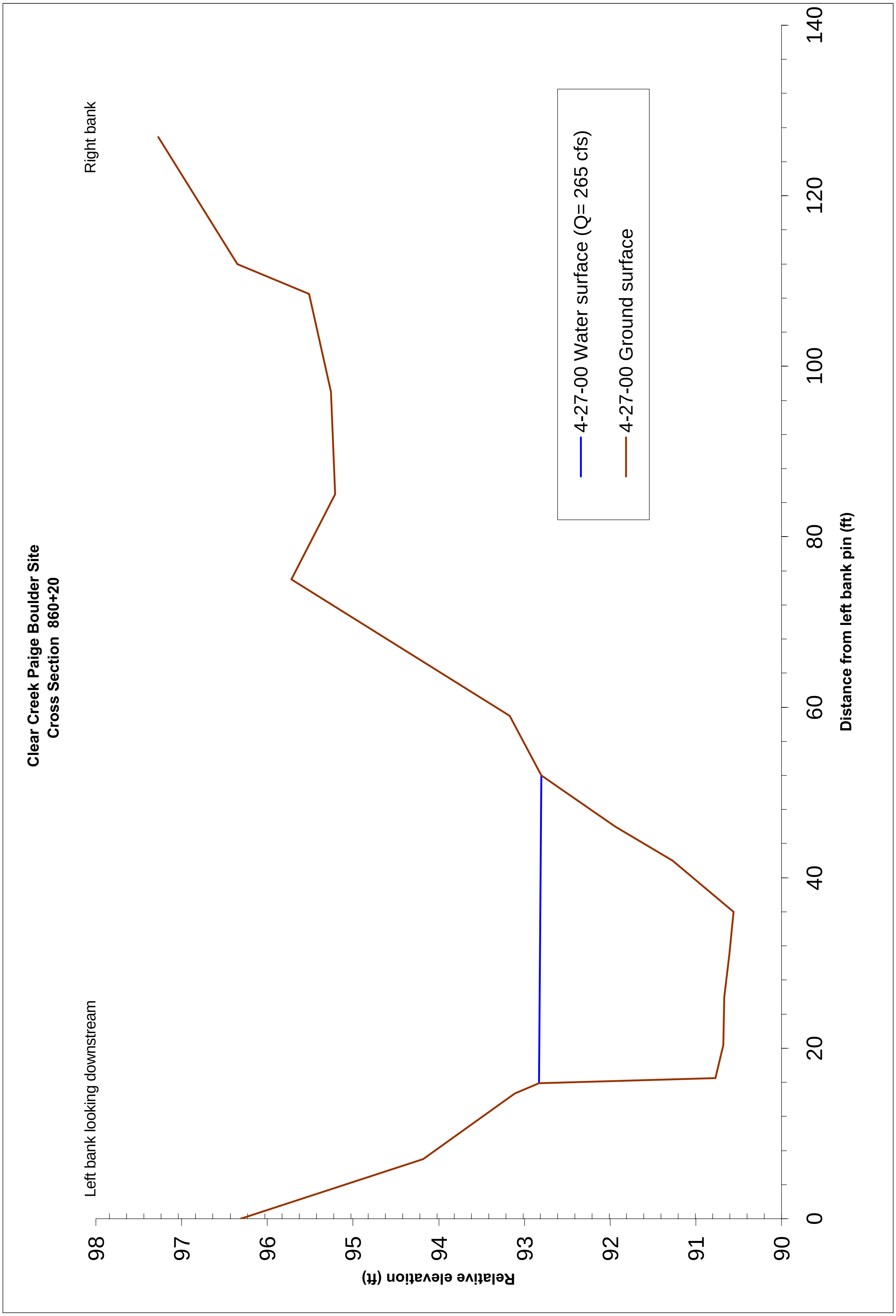

Clear Creek Paige Boulder site,
Cross Section 831+00
Left bank looking downstream
Right bank
4-26-00 Water surface (Q= 265 cfs)
4-26-00 Ground surface
Relative elevation (ft)
98
97
96
95
94
93
92
91
90
89
88
87
86
Distance from left bank pin (ft)
0
10
20
30
40
50
60
70
80
90
100

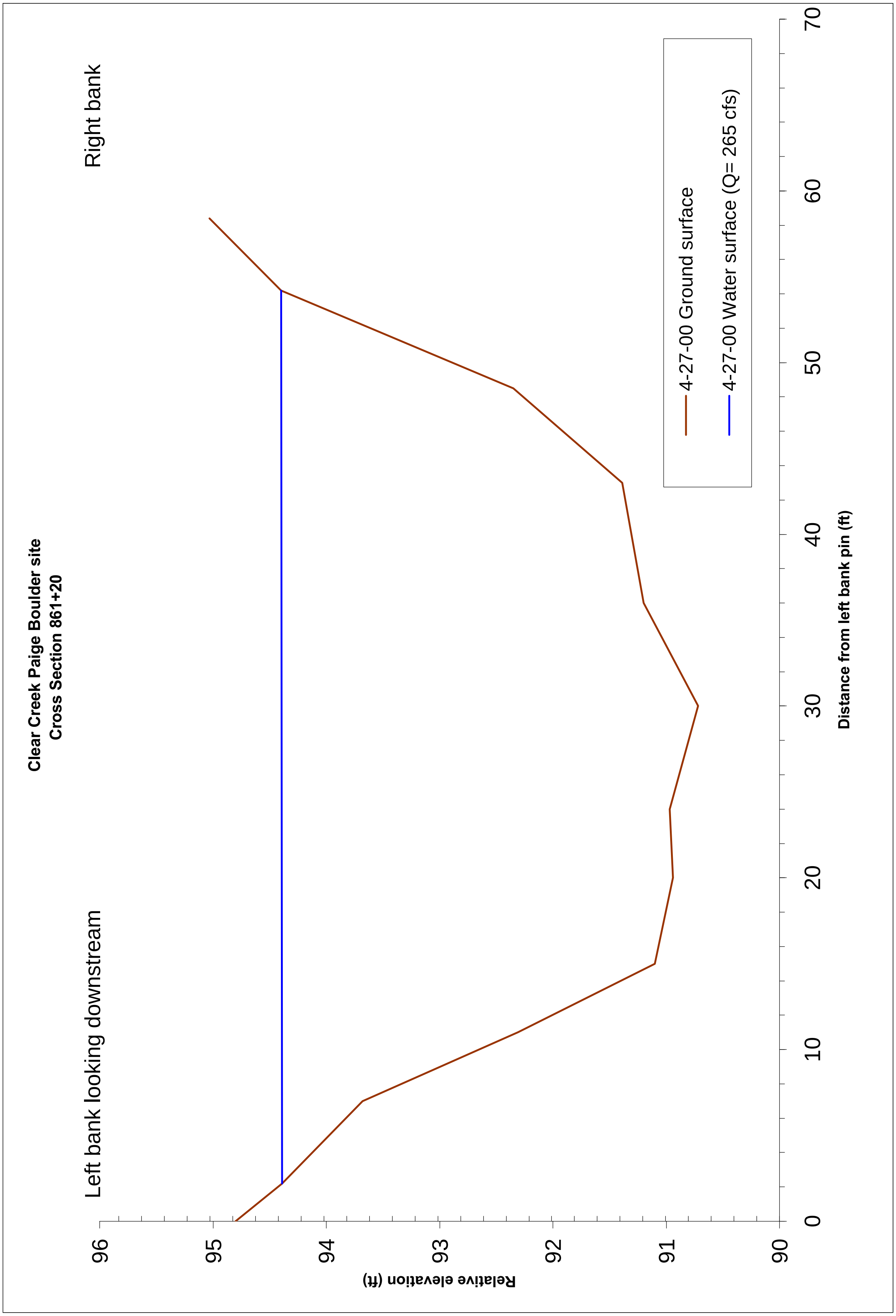

Clear Creek Paige Boulder site
Cross Section 836+50
Left bank looking downstream
Right bank
4-26-00 Ground surface
4-26-00 Water surface (Q= 265 cfs)
Relative elevation (ft)
94
93
92
91
90
89
88
87
86
85
Distance from left bank pin (ft)
0
10
20
30
40
50
60
70
80

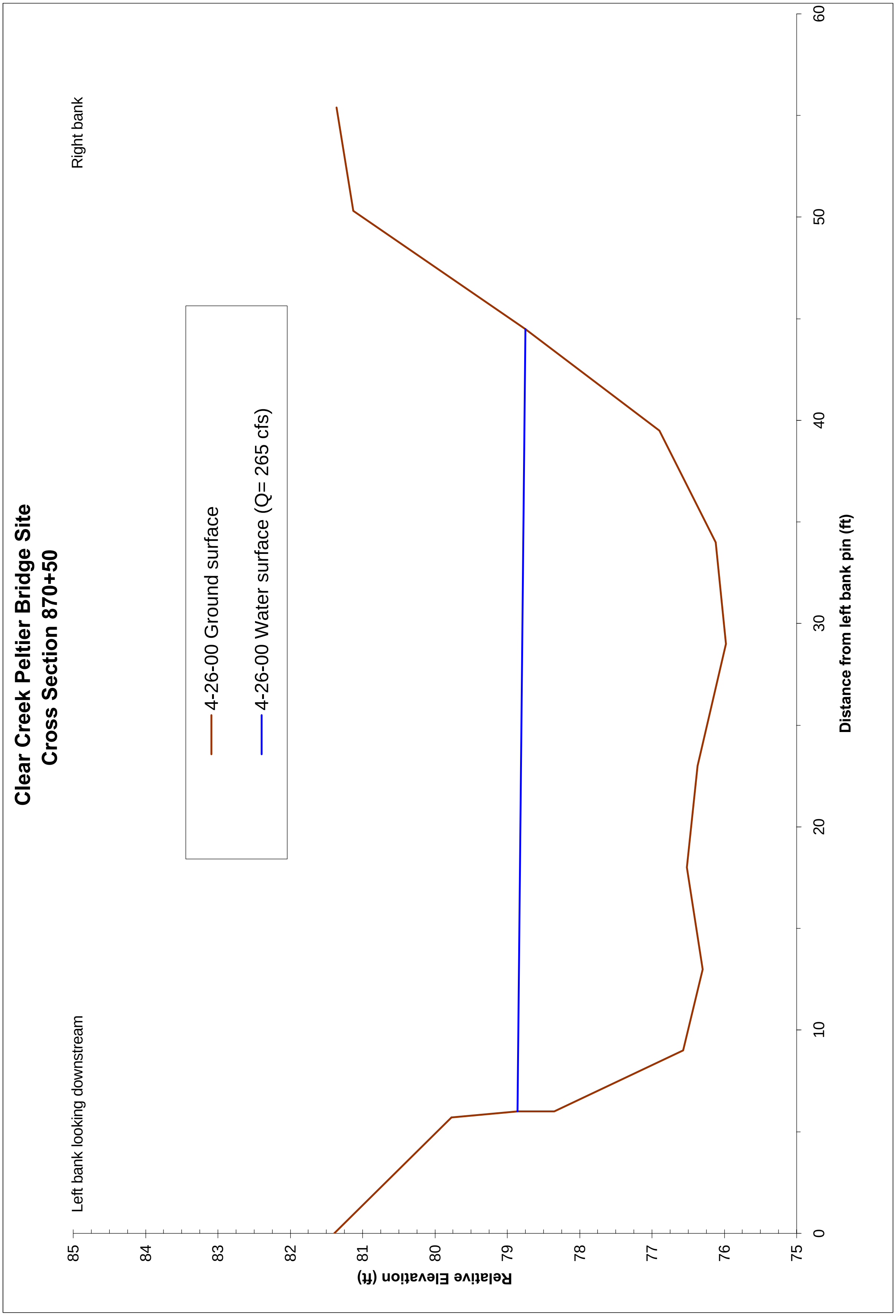

Clear Creek Paige Boulder site
Cross Section 844+00
Left bank looking downstream
Right bank
4-27-00 Water surface (Q= 265 cfs)
Ground surface after gravel transfusion
4-27-00 Ground surface
Relative elevation (ft)
920
919
918
917
916
915
914
913
912
911
910
Distance from left bank pin (ft)
0
10
20
30
40
50
60
70
80
90
100

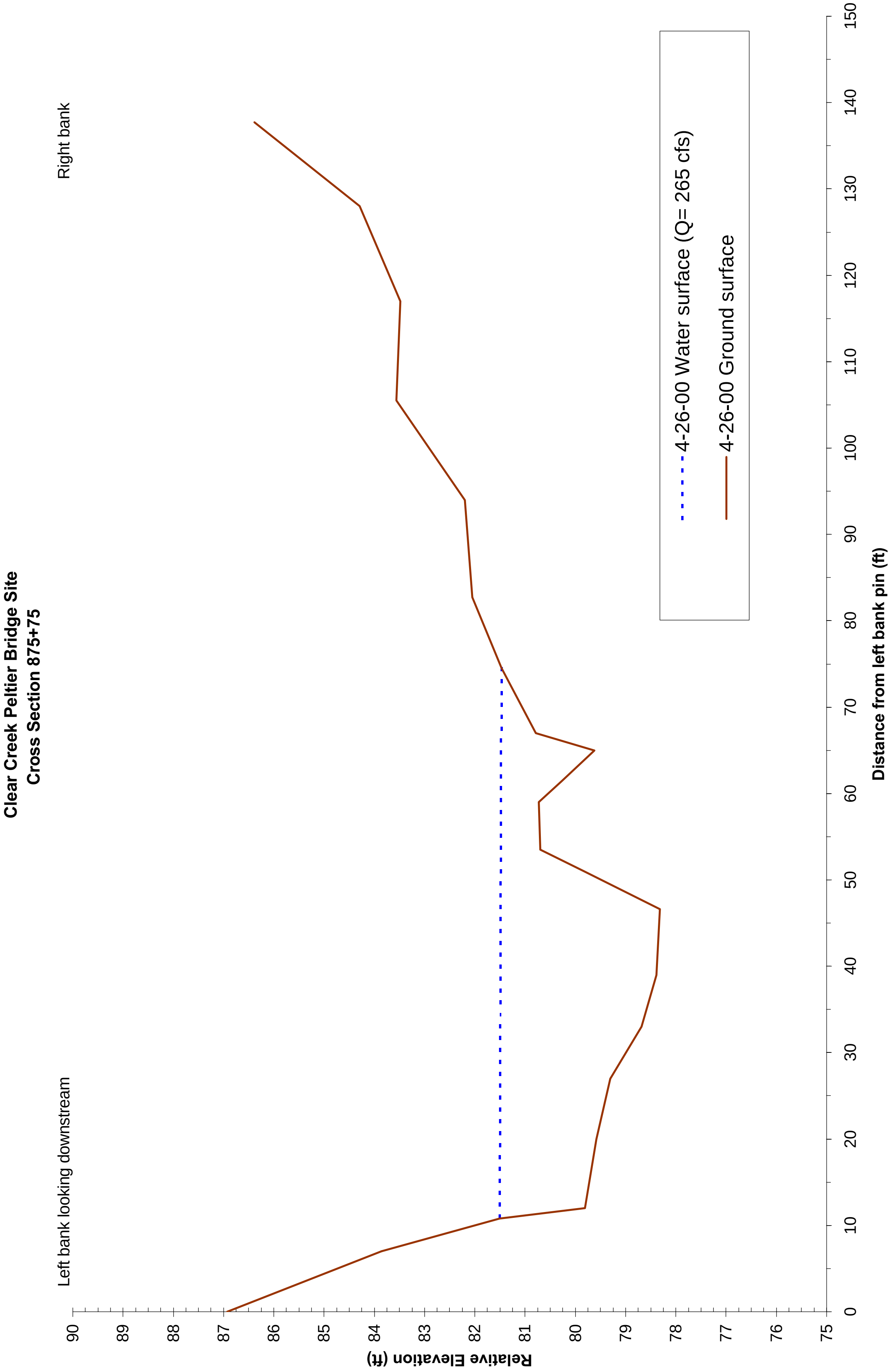

Clear Creek Paige Boulder site
Cross Section 848+00
Left bank looking downstream
Right bank
4-27-00 Ground surface
4-27-00 Water surface (Q= 265 cfs)
Relative elevation (ft)
98
97
96
95
94
93
92
91
90
Distance from left bank pin (ft)
0
50
100
150
200
250

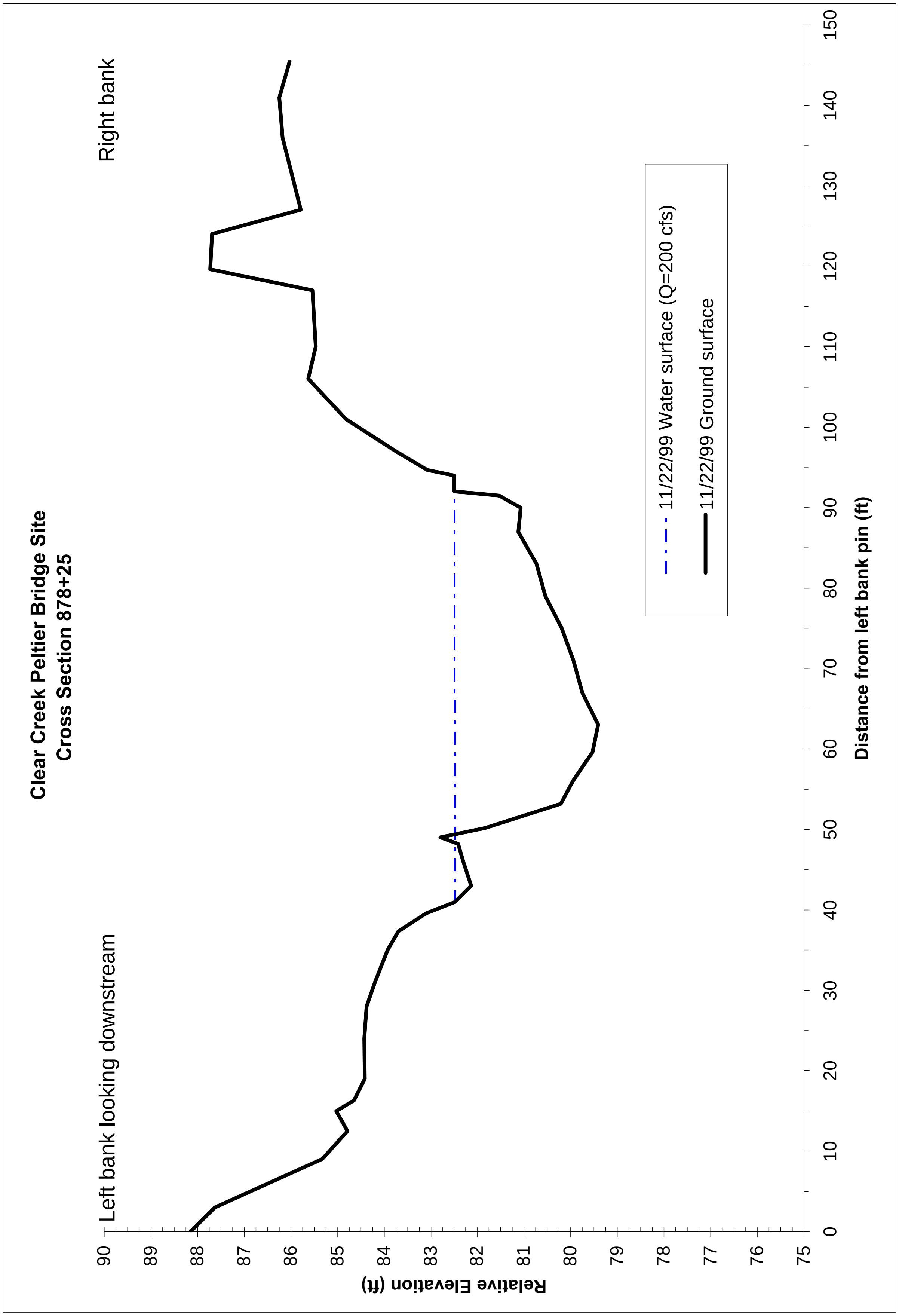

Clear Creek Paige Boulder Site
Cross section 857+50
Left bank looking downstream
Right bank
4-27-00 Ground surface
4-27-00 Water surface (Q= 265 cfs)
Relative elevation (ft)
99
97
95
93
91
89
87
85
Distance from left bank pin (ft)
0
20
40
60
80
100
120
140

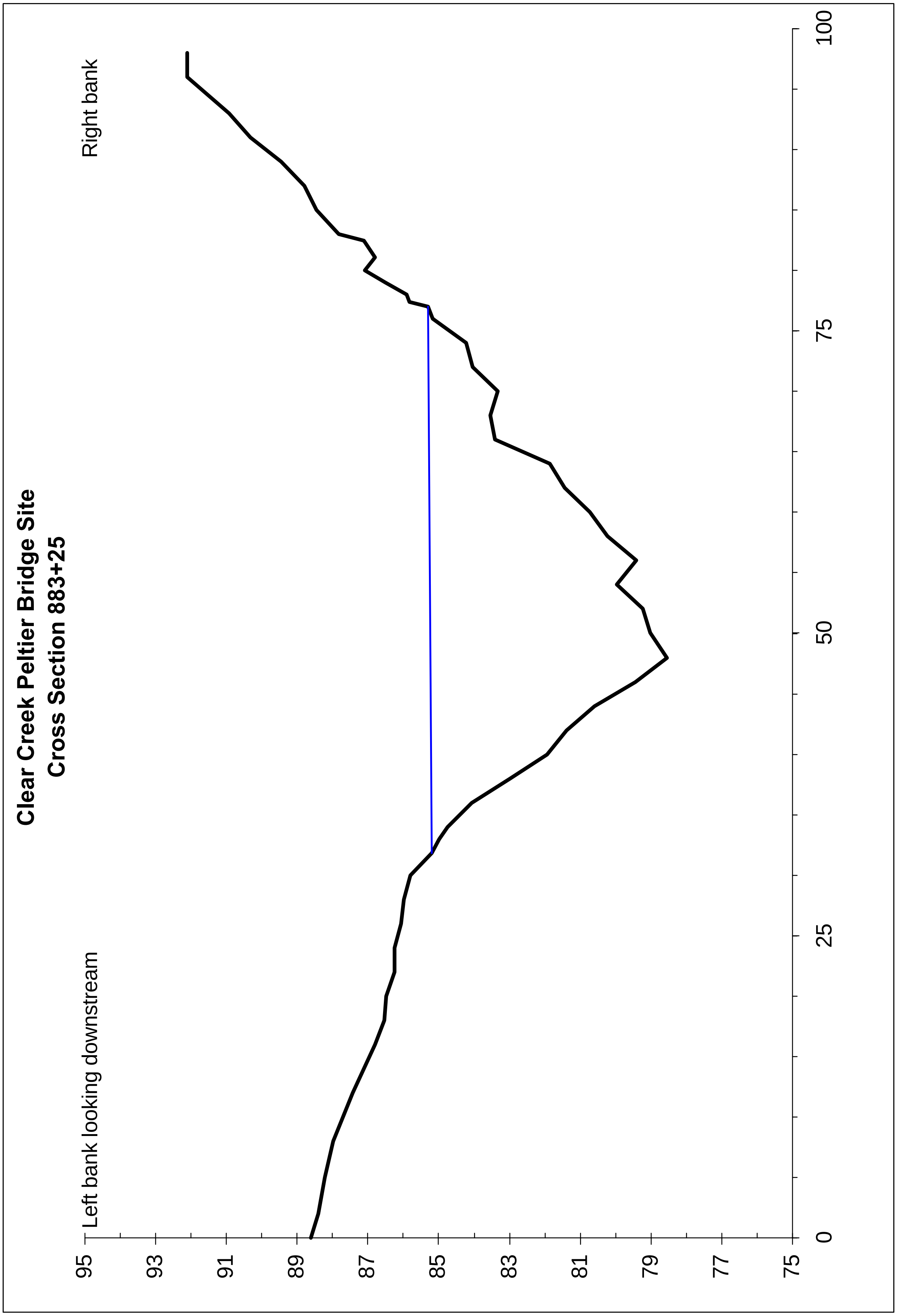

Clear Creek Paige Boulder Site
Cross Section 860+20
Left bank looking downstream
Right bank
4-27-00 Water surface (Q= 265 cfs)
4-27-00 Ground surface
Relative elevation (ft)
98
97
96
95
94
93
92
91
90
Distance from left bank pin (ft)
0
20
40
60
80
100
120
140

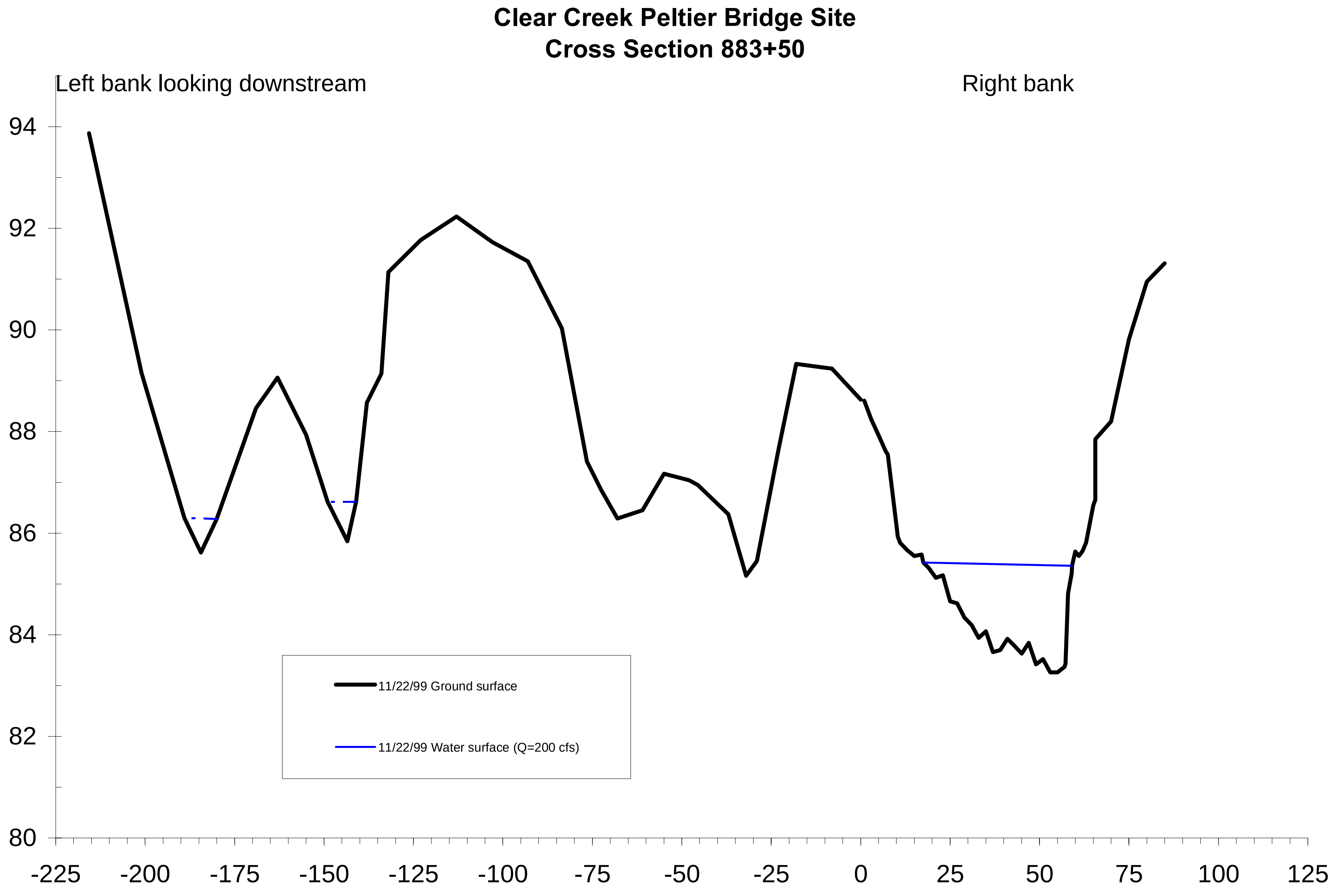

Clear Creek Paige Boulder site
Cross Section 861+20
Left bank looking downstream
Right bank
4-27-00 Ground surface
4-27-00 Water surface (Q= 265 cfs)
Relative elevation (ft)
96
95
94
93
92
91
90
Distance from left bank pin (ft)
0
10
20
30
40
50
60
70

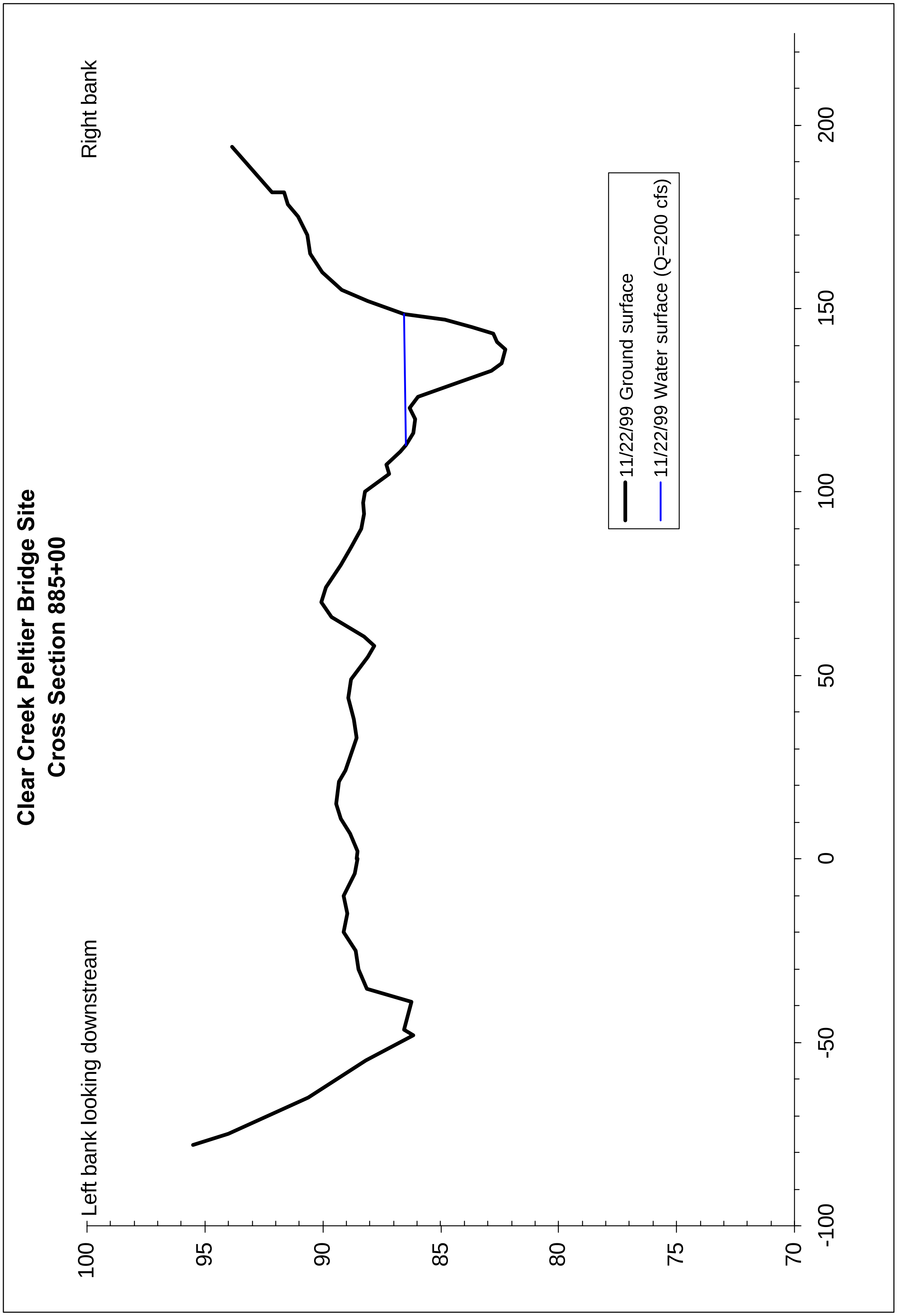

Clear Creek Peltier Bridge Site
Cross Section 870+50
4-26-00 Ground surface
4-26-00 Water surface (Q= 265 cfs)
Left bank looking downstream
Right bank
Relative Elevation (ft)
85
84
83
82
81
80
79
78
77
76
75
Distance from left bank pin (ft)
0
10
20
30
40
50
60

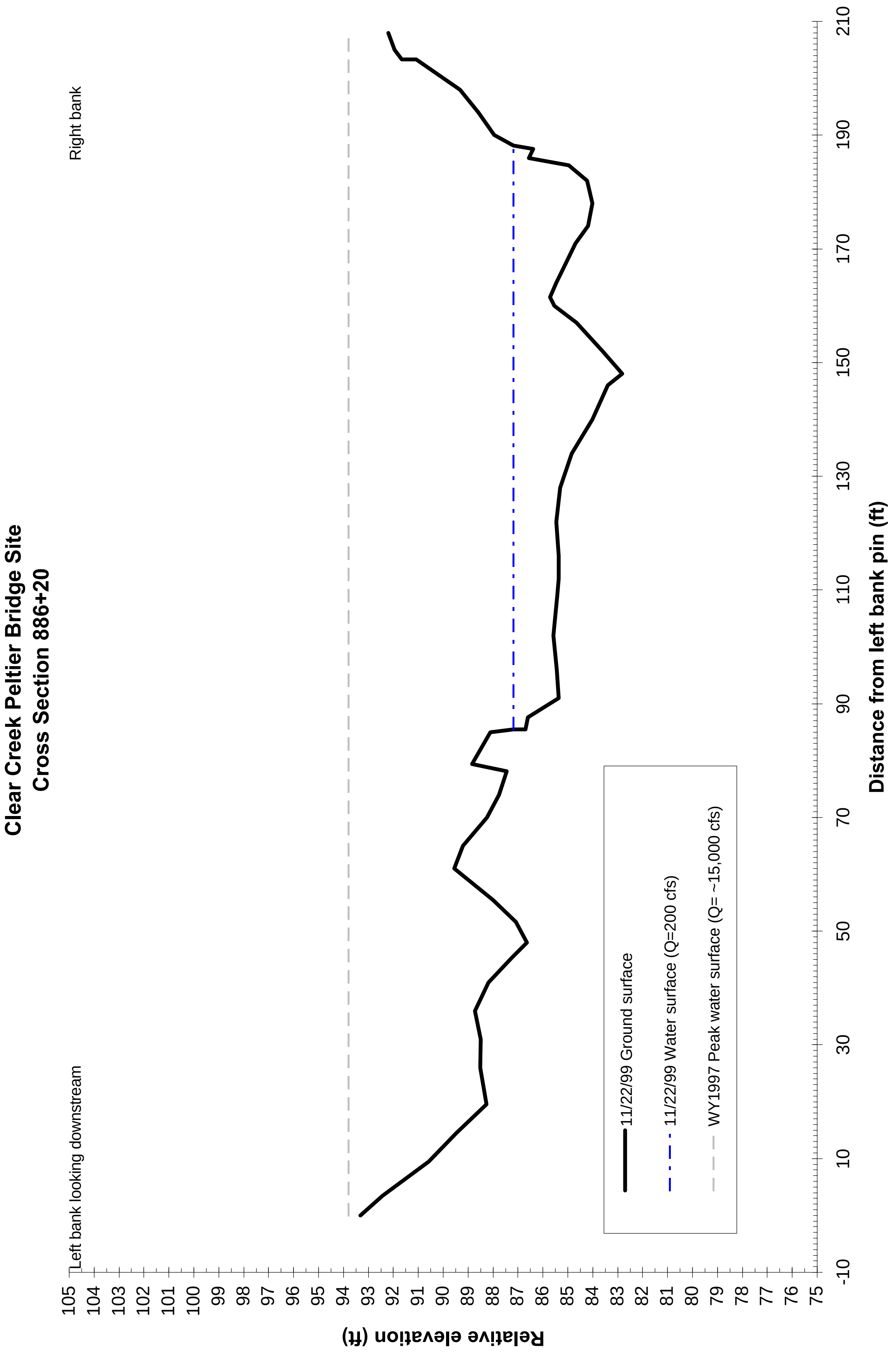

Clear Creek Peltier Bridge Site
Cross Section 875+75
Left bank looking downstream
Right bank
4-26-00 Water surface (Q= 265 cfs)
4-26-00 Ground surface
Relative Elevation (ft)
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
Distance from left bank pin (ft)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

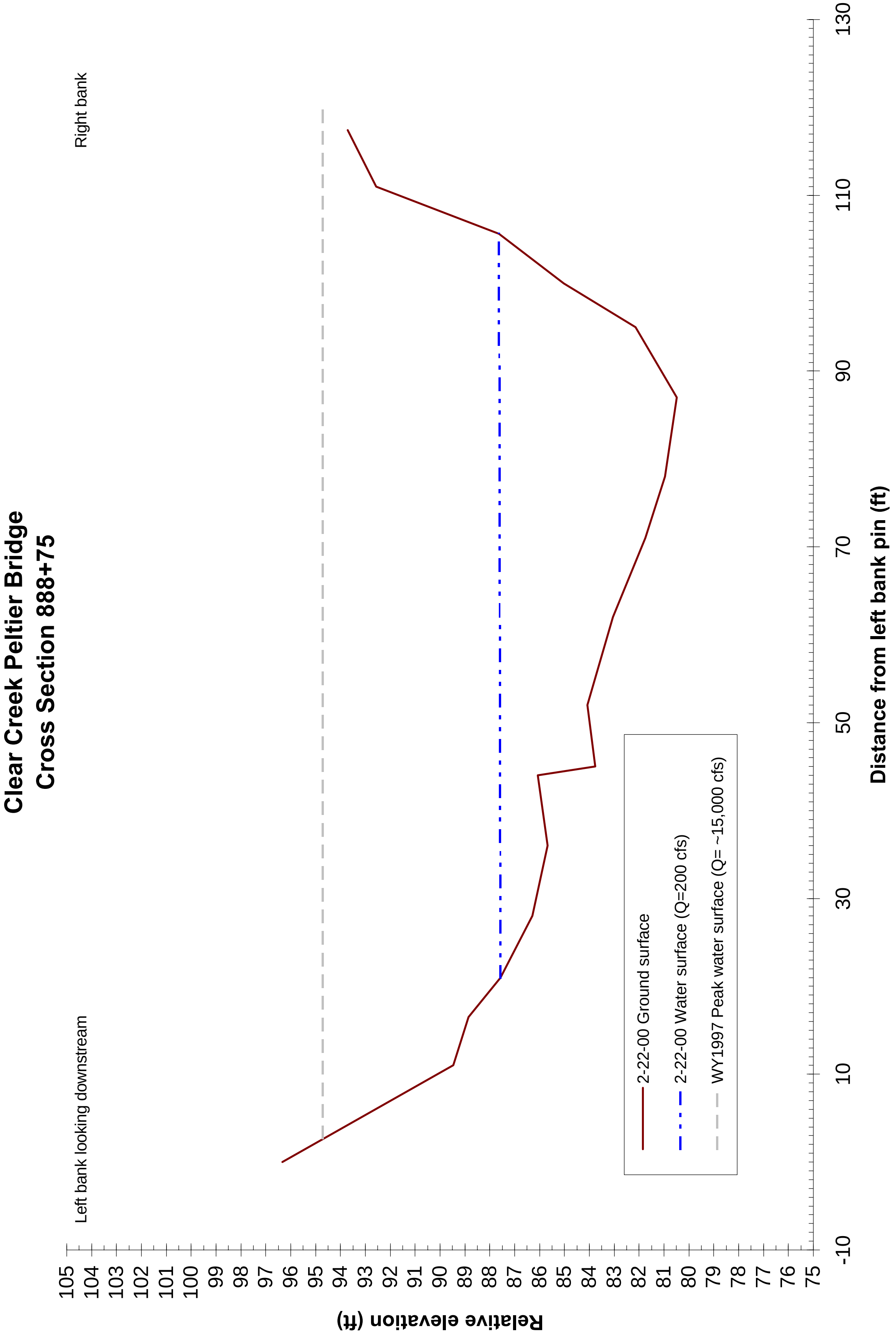

Clear Creek Peltier Bridge Site
Cross Section 878+25
Left bank looking downstream
Right bank
11/22/99 Water surface (Q=200 cfs)
11/22/99 Ground surface
Relative Elevation (ft)
Distance from left bank pin (ft)
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150


Clear Creek Peltier Bridge Site
Cross Section 883+25
Left bank looking downstream
Right bank
95
93
91
89
87
85
83
81
79
77
75
0
25
50
75
100

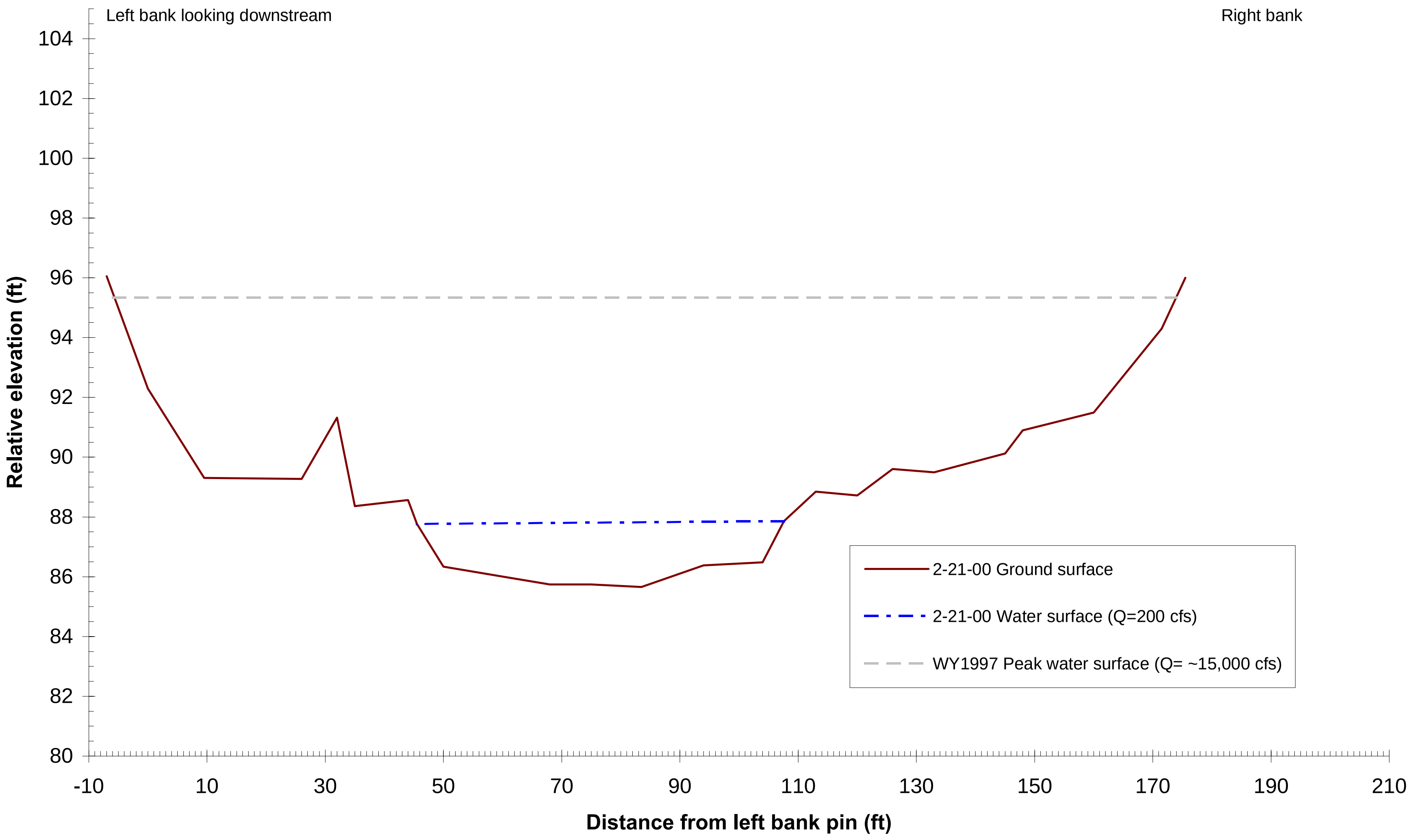

Clear Creek Peltier Bridge Site
Cross Section 883+50
Left bank looking downstream
Right bank
94
92
90
88
86
84
82
80
-225
-200
-175
-150
-125
-100
-75
-50
-25
0
25
50
75
100
125
11/22/99 Ground surface
11/22/99 Water surface (Q=200 cfs)

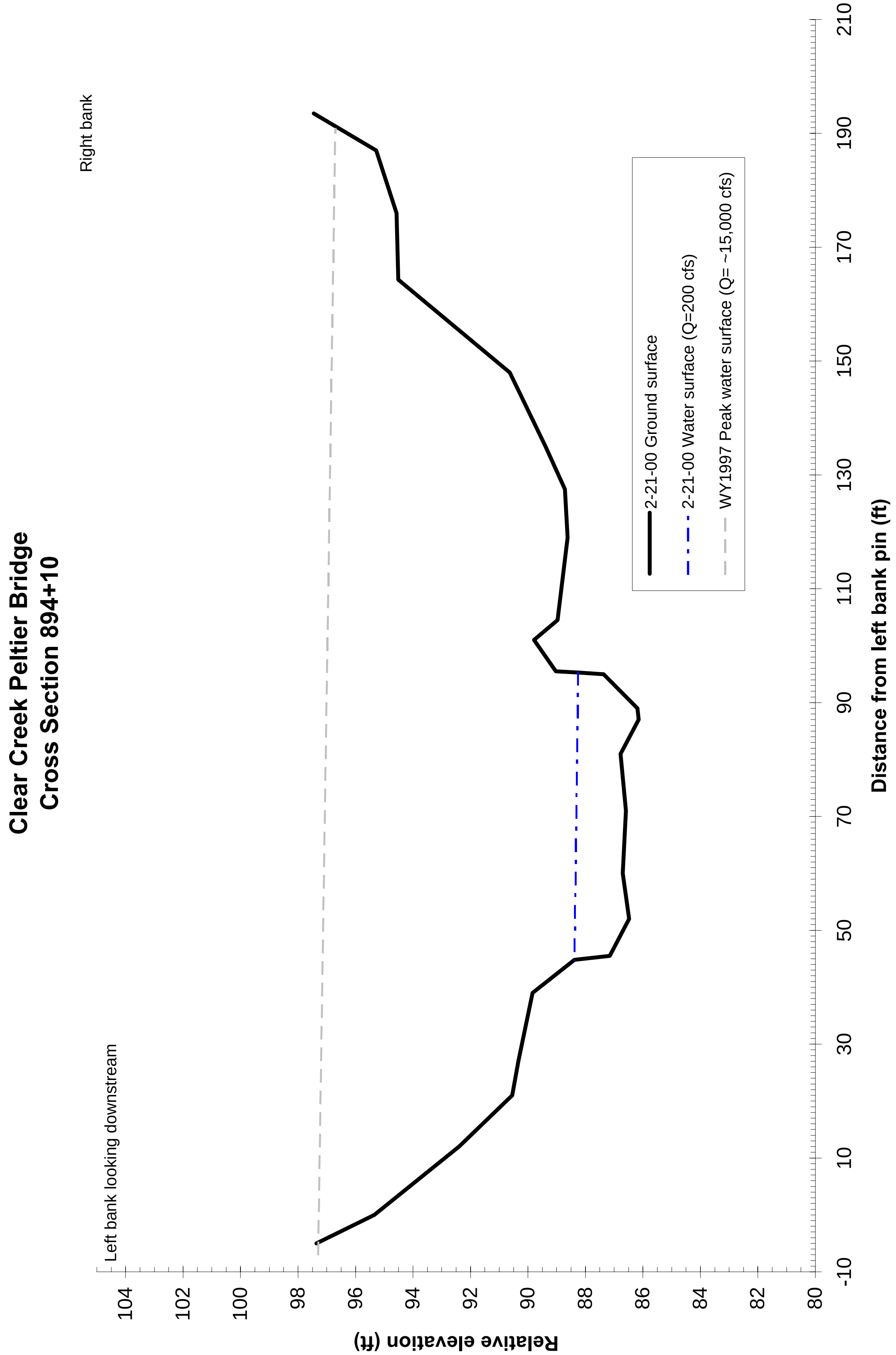

Clear Creek Peltier Bridge Site
Cross Section 885+00
Left bank looking downstream
Right bank
11/22/99 Ground surface
11/22/99 Water surface (Q=200 cfs)
100
95
90
85
80
75
70
-100
-50
0
50
100
150
200

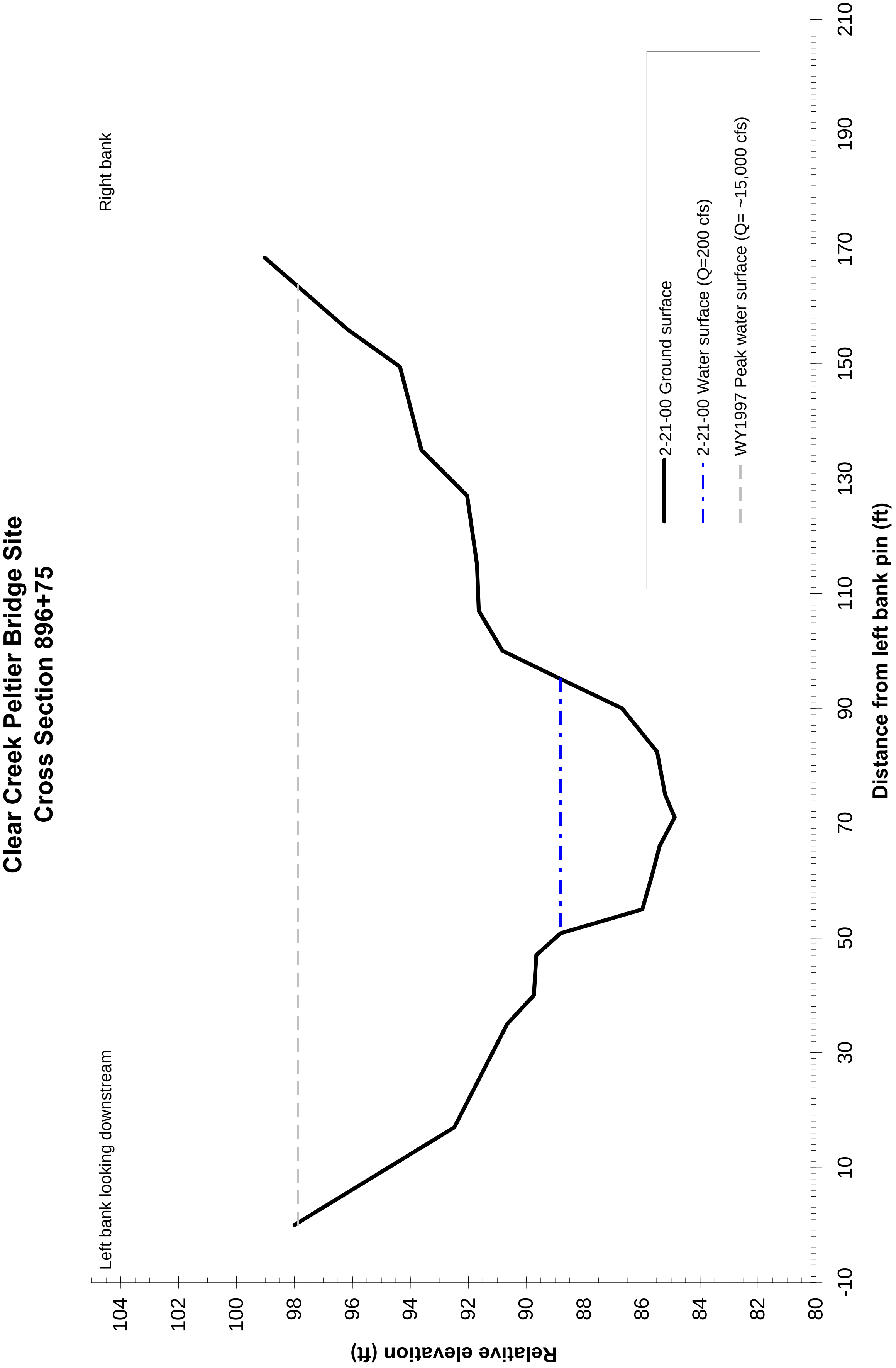

Clear Creek Peltier Bridge Site
Cross Section 886+20
Left bank looking downstream
Right bank
11/22/99 Ground surface
11/22/99 Water surface (Q=200 cfs)
WY1997 Peak water surface (Q= ~15,000 cfs)
Relative elevation (ft)
105
104
103
102
101
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
Distance from left bank pin (ft)
-10
10
30
50
70
90
110
130
150
170
190
210


Clear Creek Peltier Bridge
Cross Section 888+75
Left bank looking downstream
Right bank
2-22-00 Ground surface
2-22-00 Water surface (Q=200 cfs)
WY1997 Peak water surface (Q= ~15,000 cfs)
Relative elevation (ft)
105
104
103
102
101
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
Distance from left bank pin (ft)
-10
10
30
50
70
90
110
130

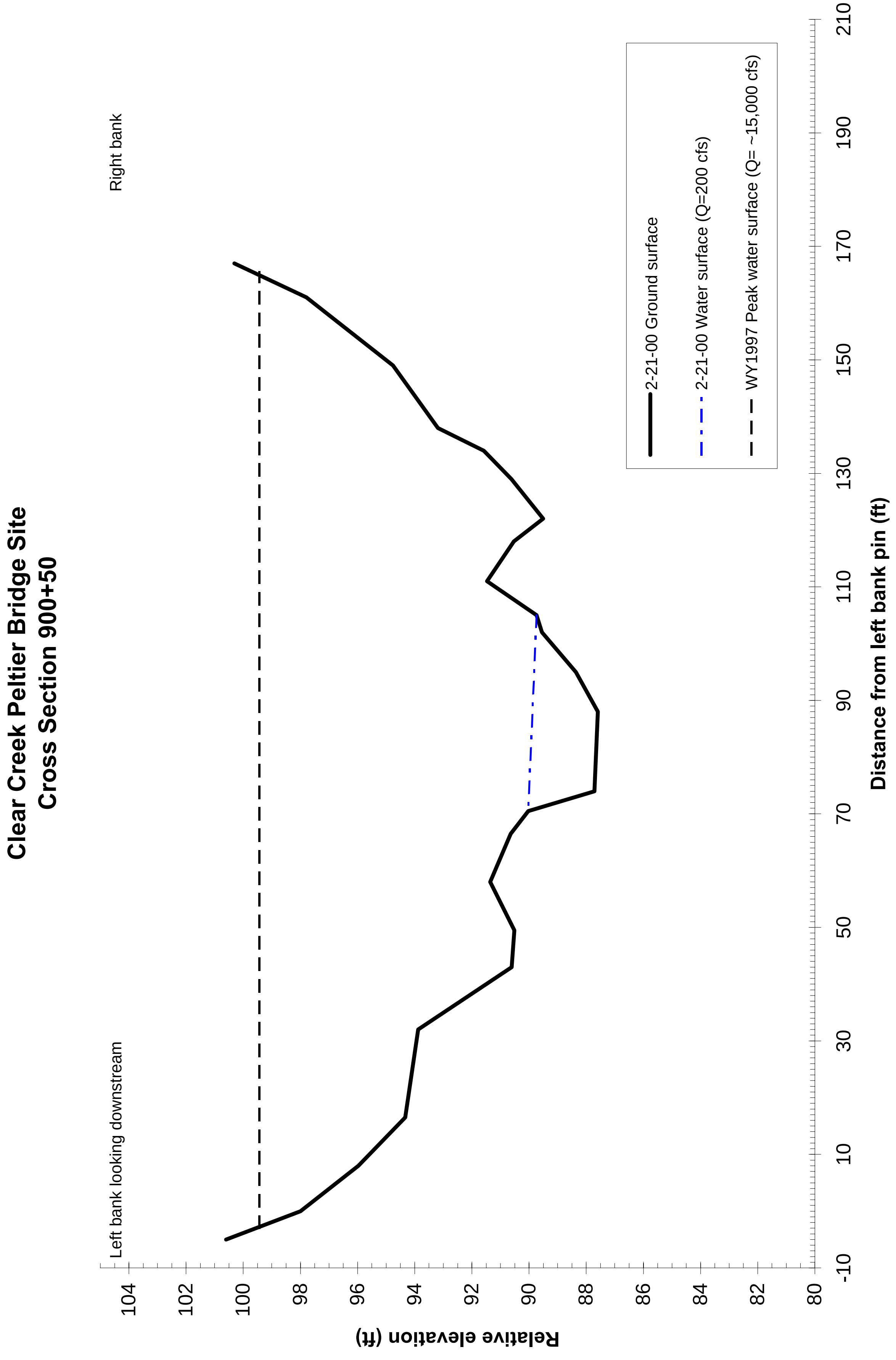
Clear Creek Peltier Bridge
Cross Section 891+80

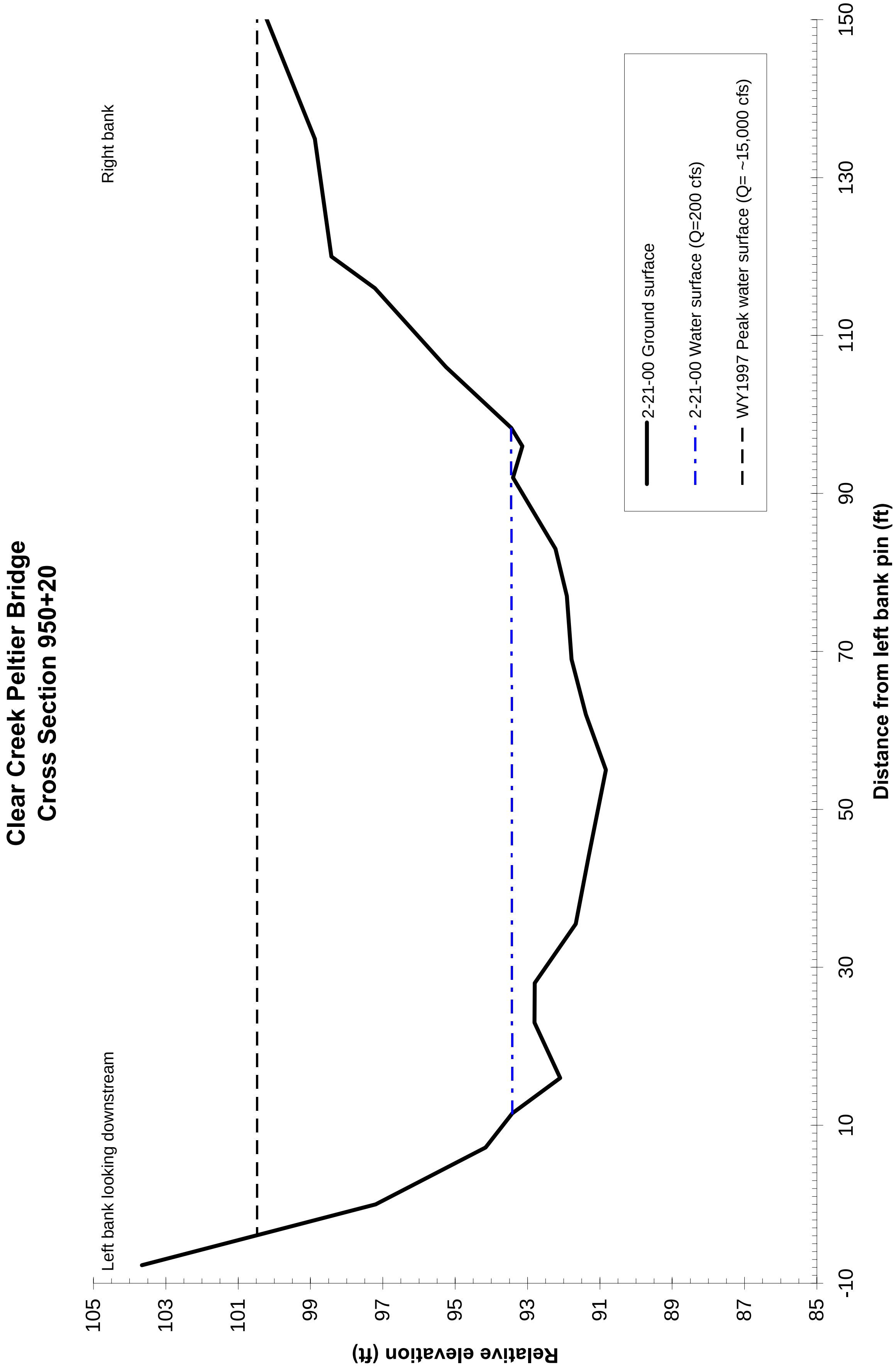



Clear Creek Peltier Bridge
Cross Section 894+10
Left bank looking downstream
Right bank
2-21-00 Ground surface
2-21-00 Water surface (Q=200 cfs)
WY1997 Peak water surface (Q= ~15,000 cfs)
Relative elevation (ft)
80
82
84
86
88
90
92
94
96
98
100
102
104
Distance from left bank pin (ft)
-10
10
30
50
70
90
110
130
150
170
190
210

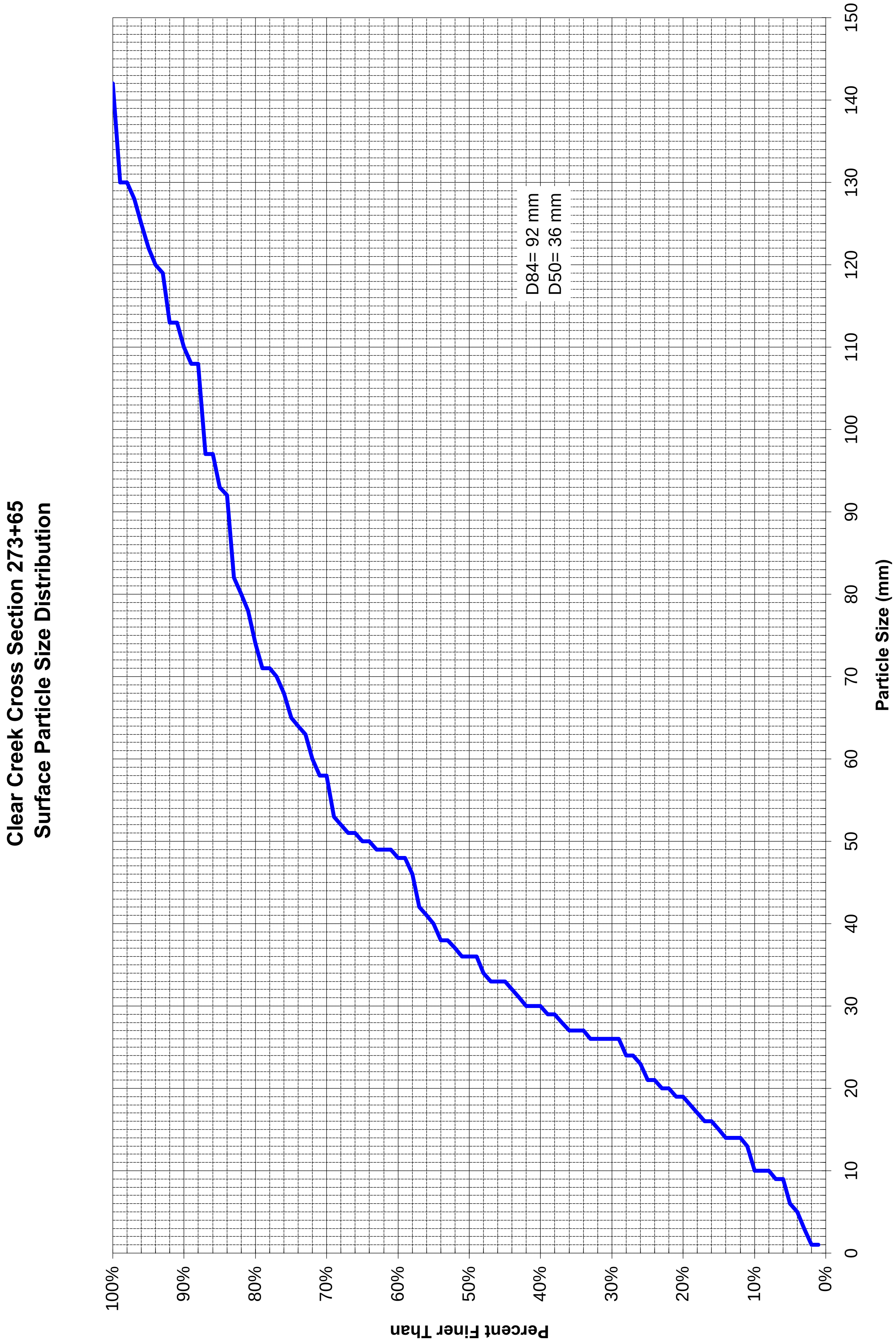


Clear Creek Peltier Bridge Site
Cross Section 896+75

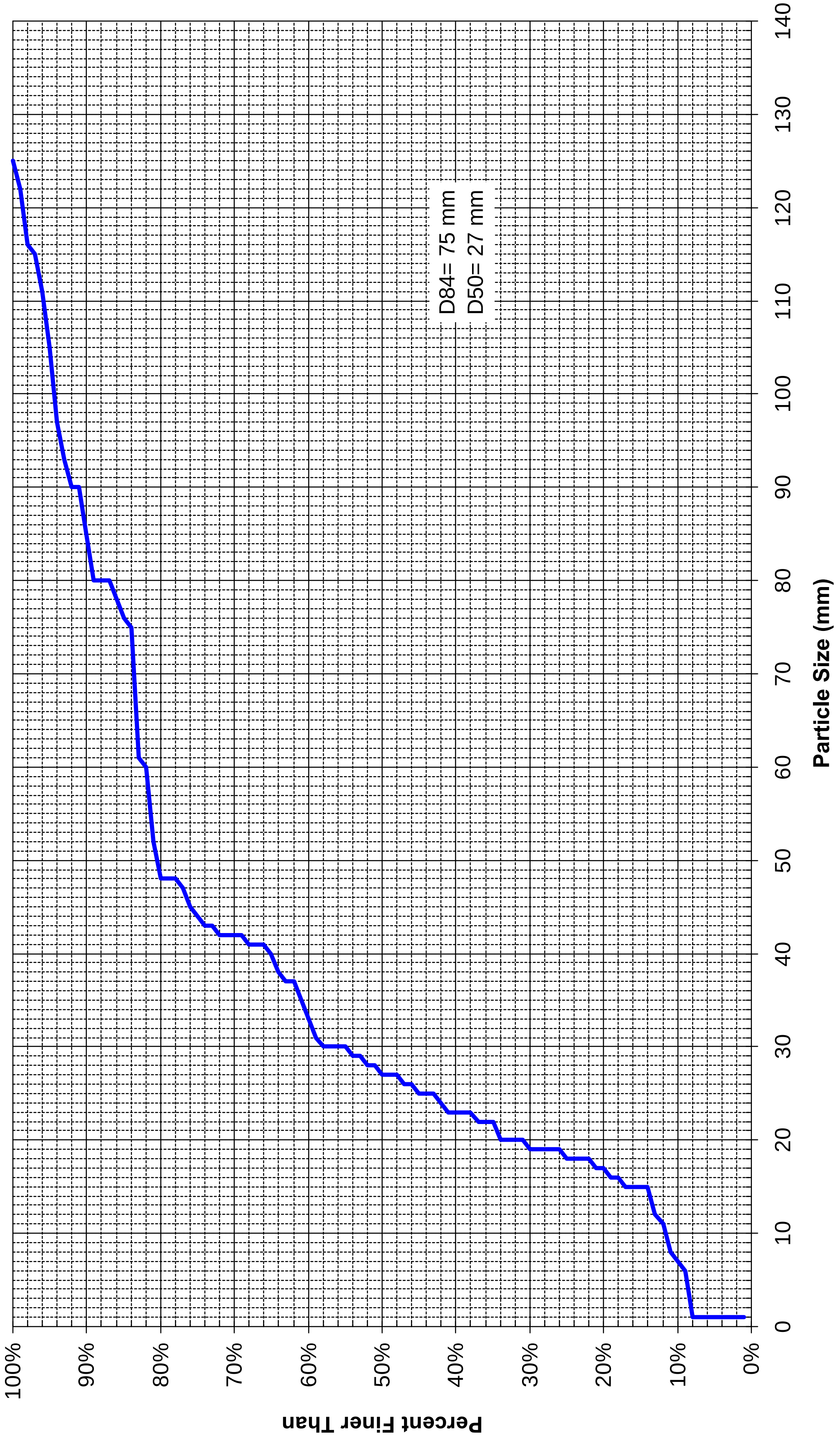

Clear Creek Peltier Bridge Site
Cross Section 900+50
Left bank looking downstream
Right bank
2-21-00 Ground surface
2-21-00 Water surface (Q=200 cfs)
WY1997 Peak water surface (Q= ~15,000 cfs)
Relative elevation (ft)
104
102
100
98
96
94
92
90
88
86
84
82
80
Distance from left bank pin (ft)
-10
10
30
50
70
90
110
130
150
170
190
210

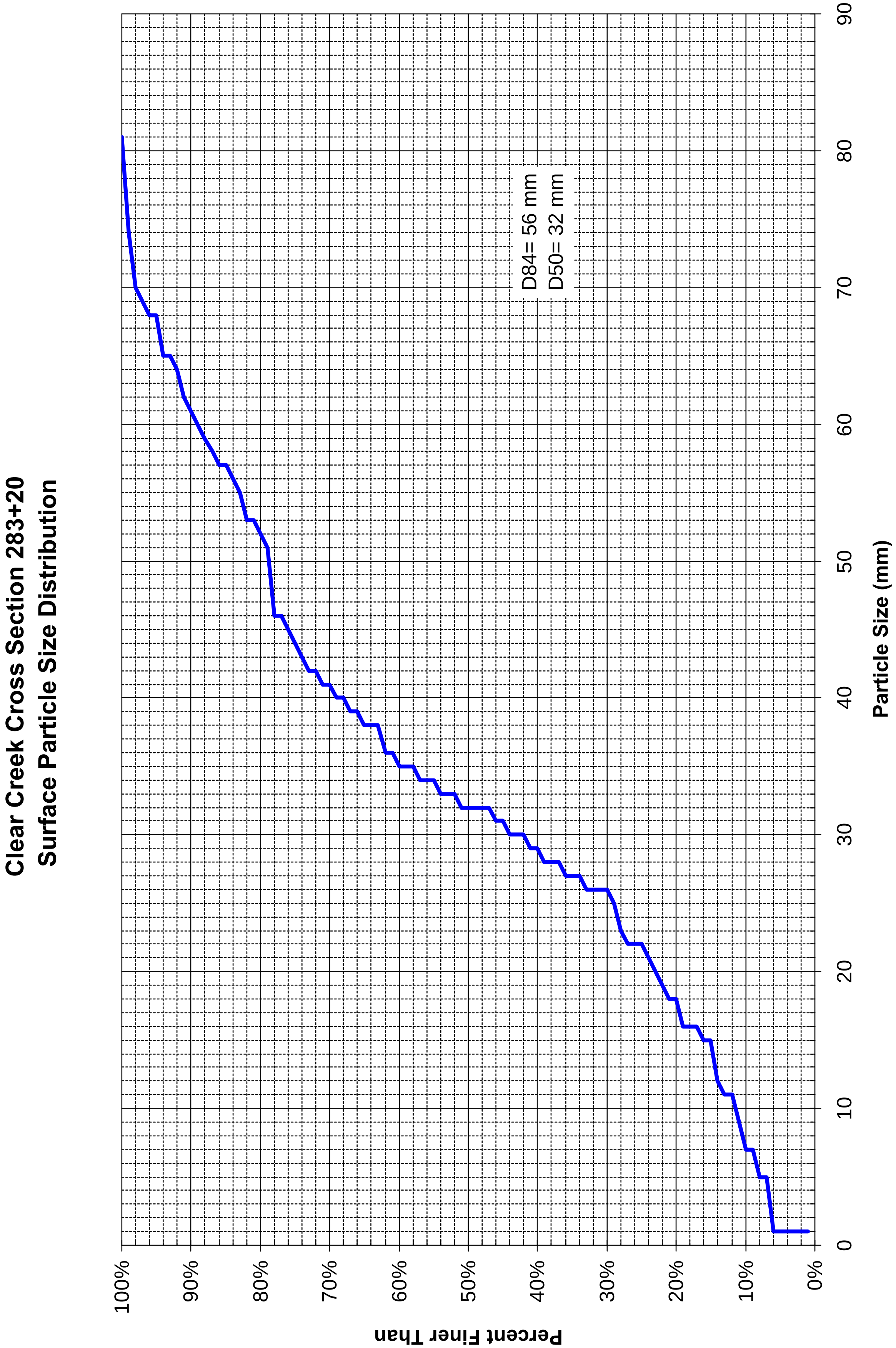


Clear Creek Peltier Bridge
Cross Section 950+20


Clear Creek Cross Section 273+65
Surface Particle Size Distribution
D84= 92 mm
D50= 36 mm
Percent Finer Than
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Particle Size (mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

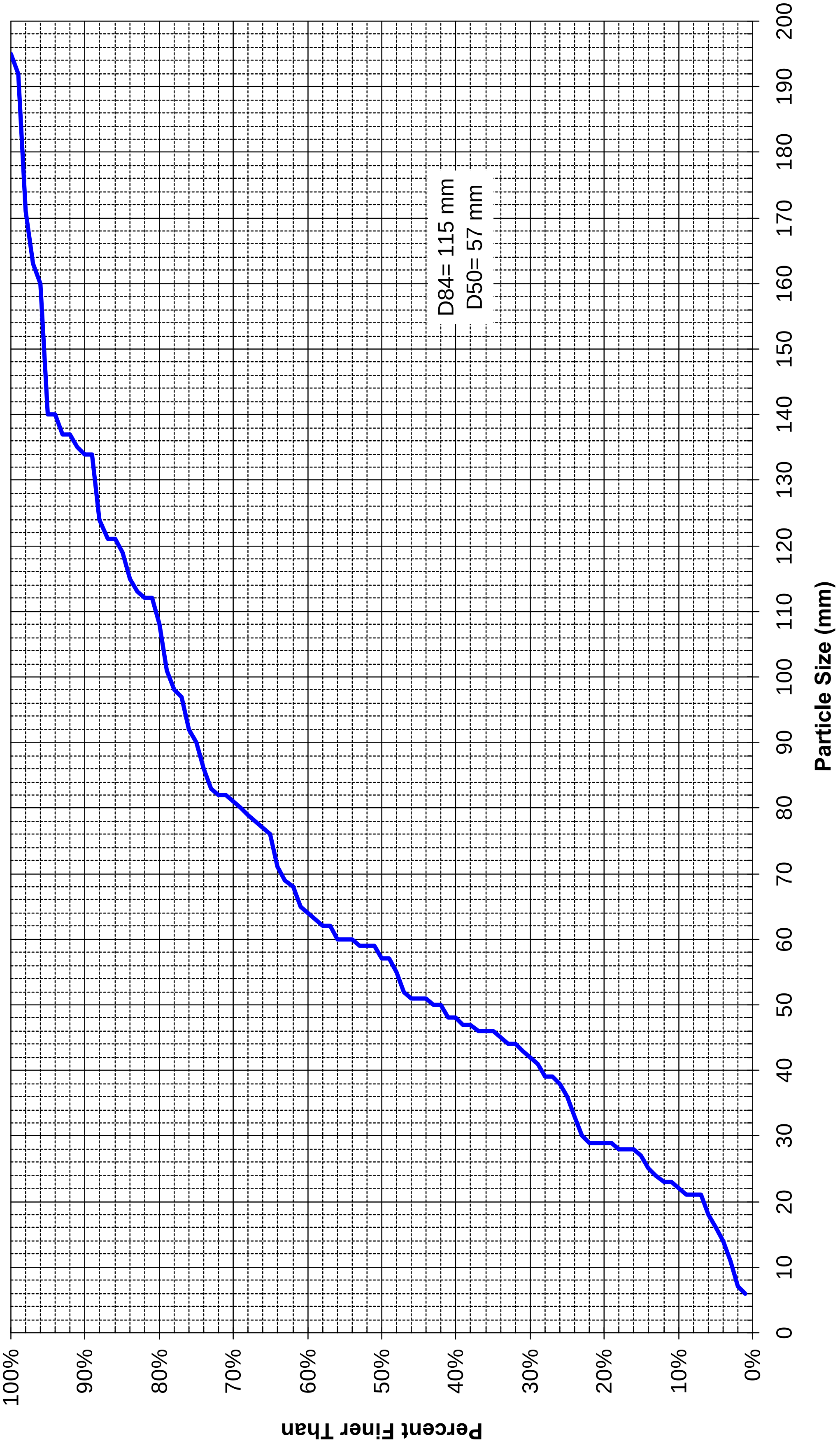
Clear Creek Cross Section 277+55
Surface Particle Size Distribution

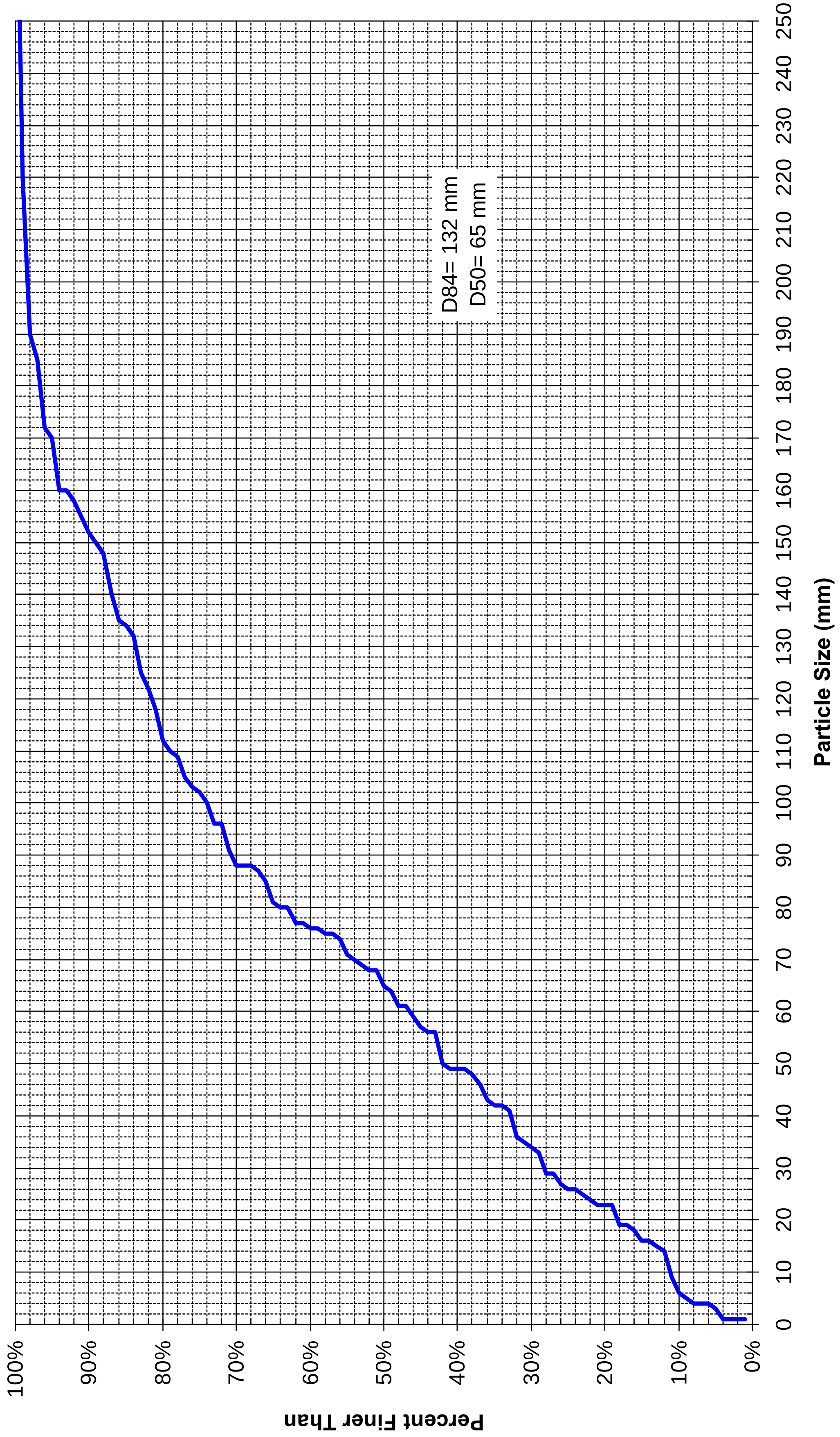




Clear Creek Cross Section 283+20
Surface Particle Size Distribution

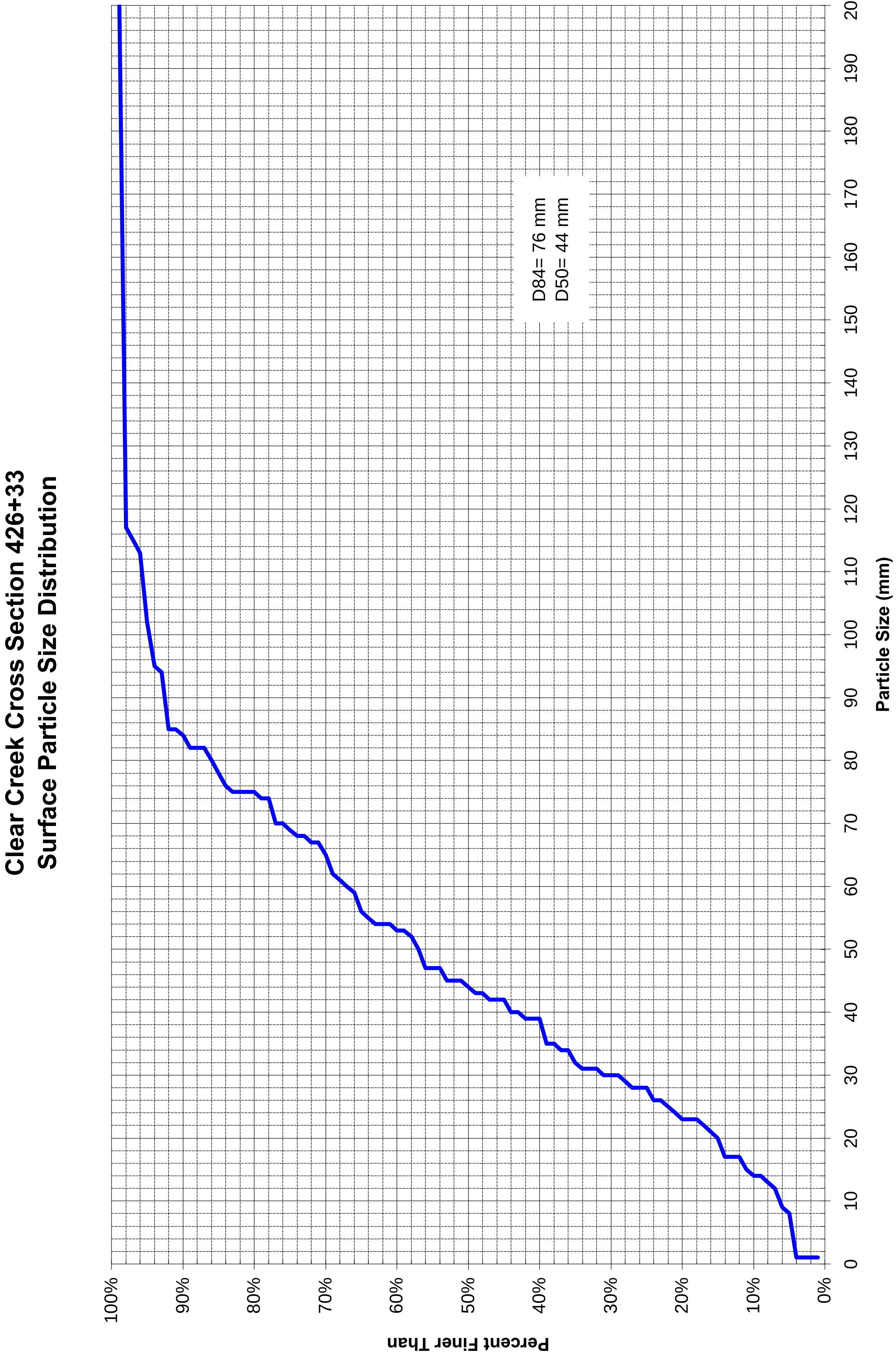
Clear Creek Cross Section 410+26
Surface Particle Size Distribution

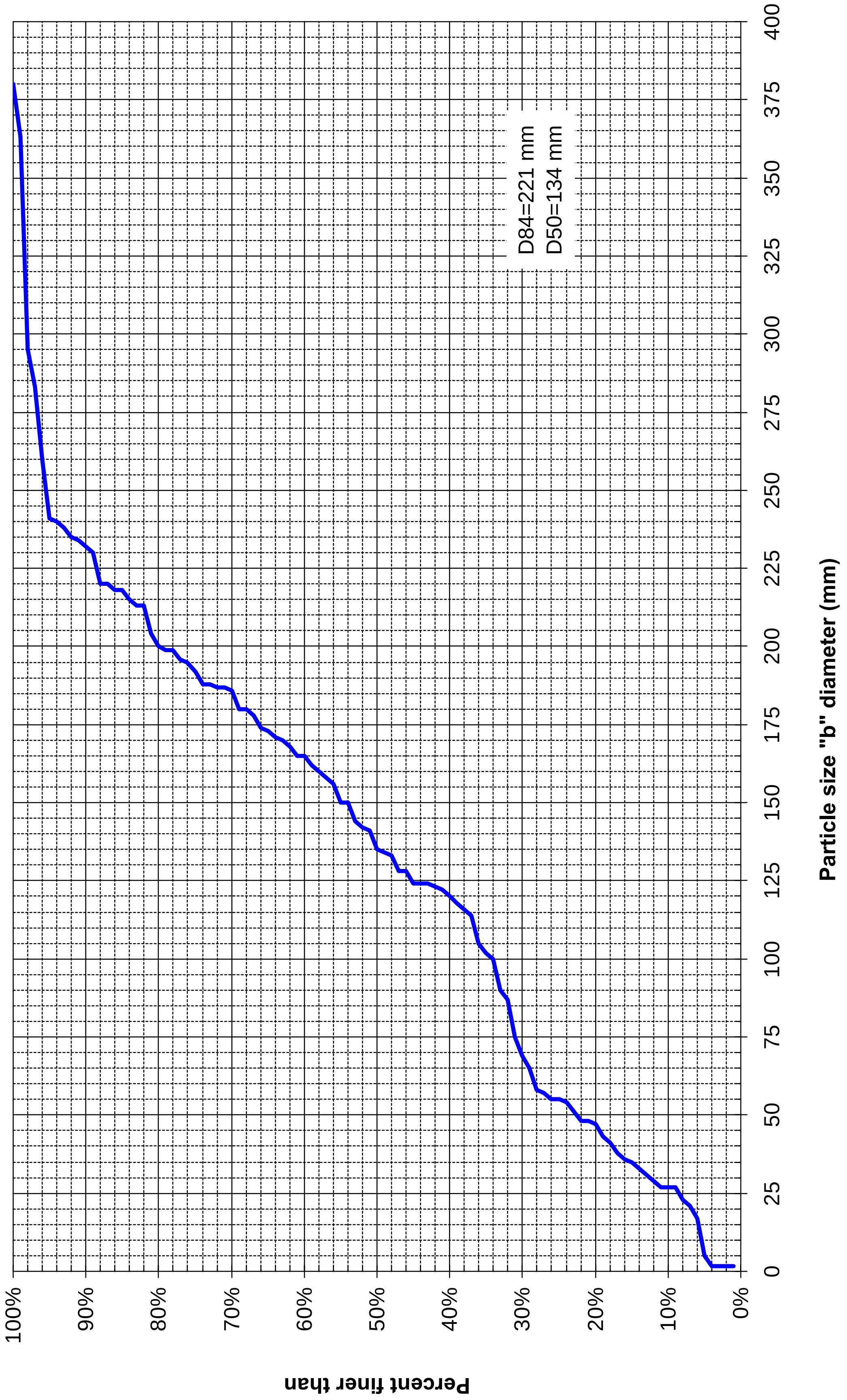




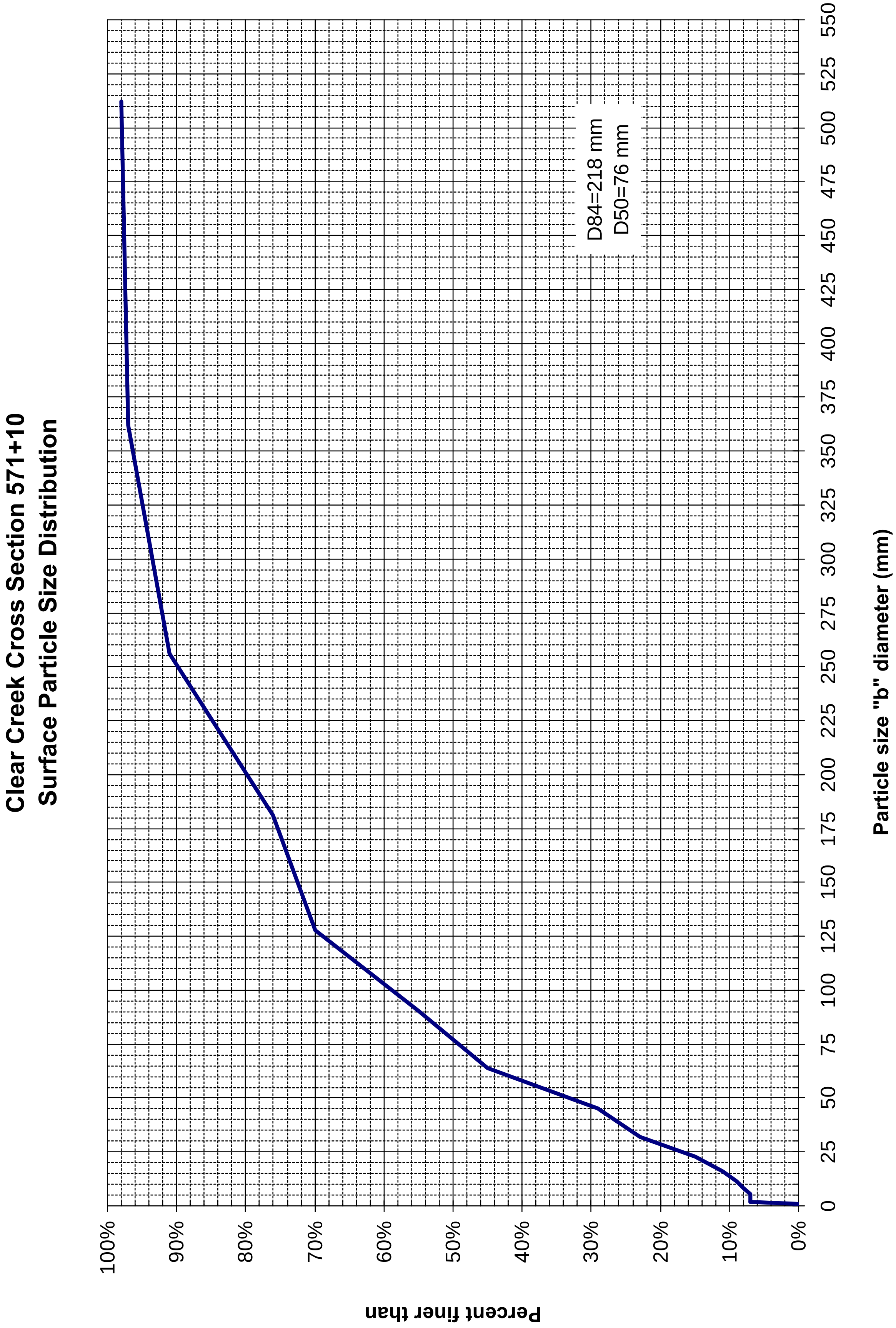
Clear Creek Cross Section 411+66
Surface Particle Size Distribution

D84= 132 mm
D50= 65 mm

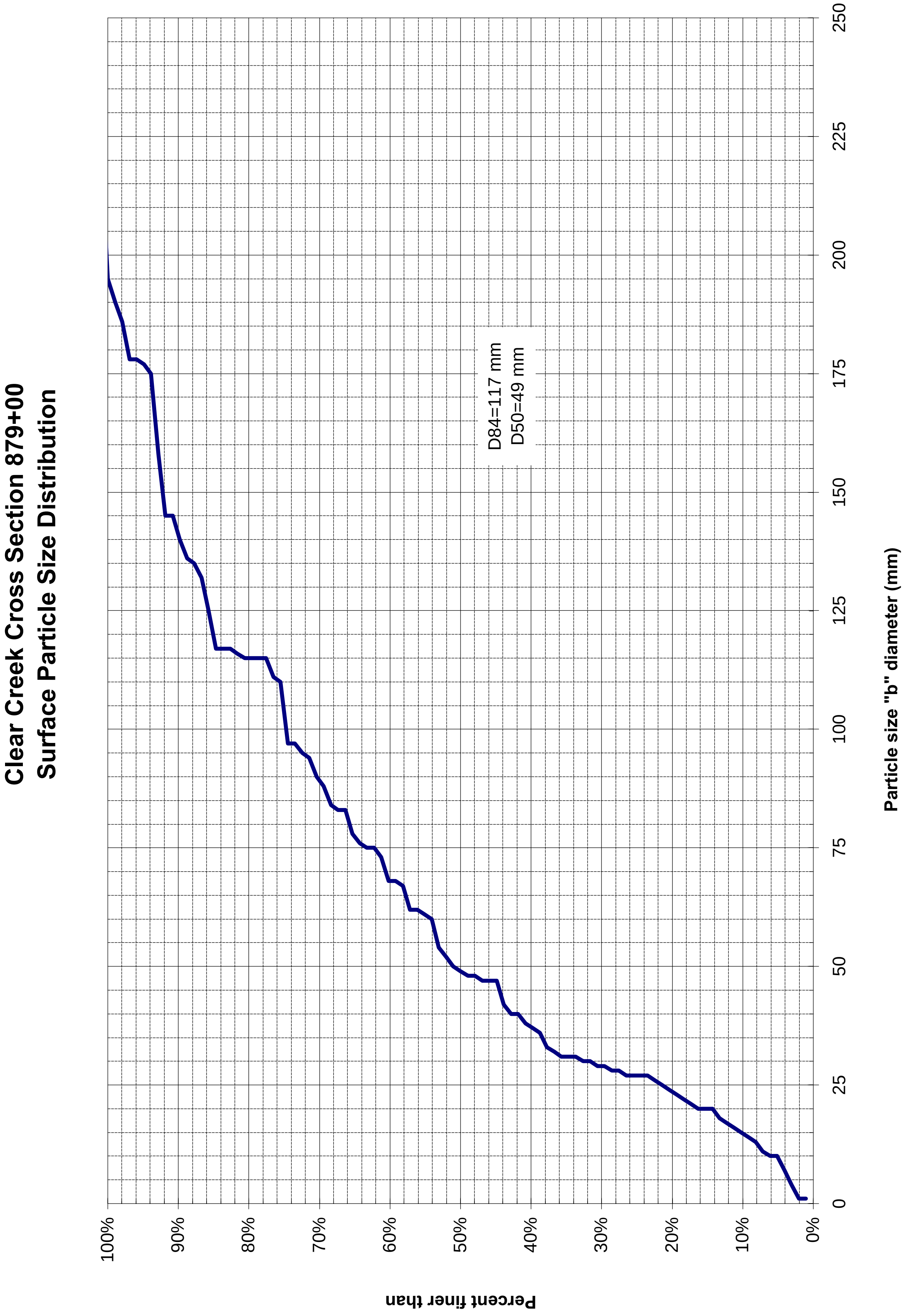

Clear Creek Cross Section 426+33
Surface Particle Size Distribution
D84= 76 mm
D50= 44 mm
Percent Finer Than
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Particle Size (mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200



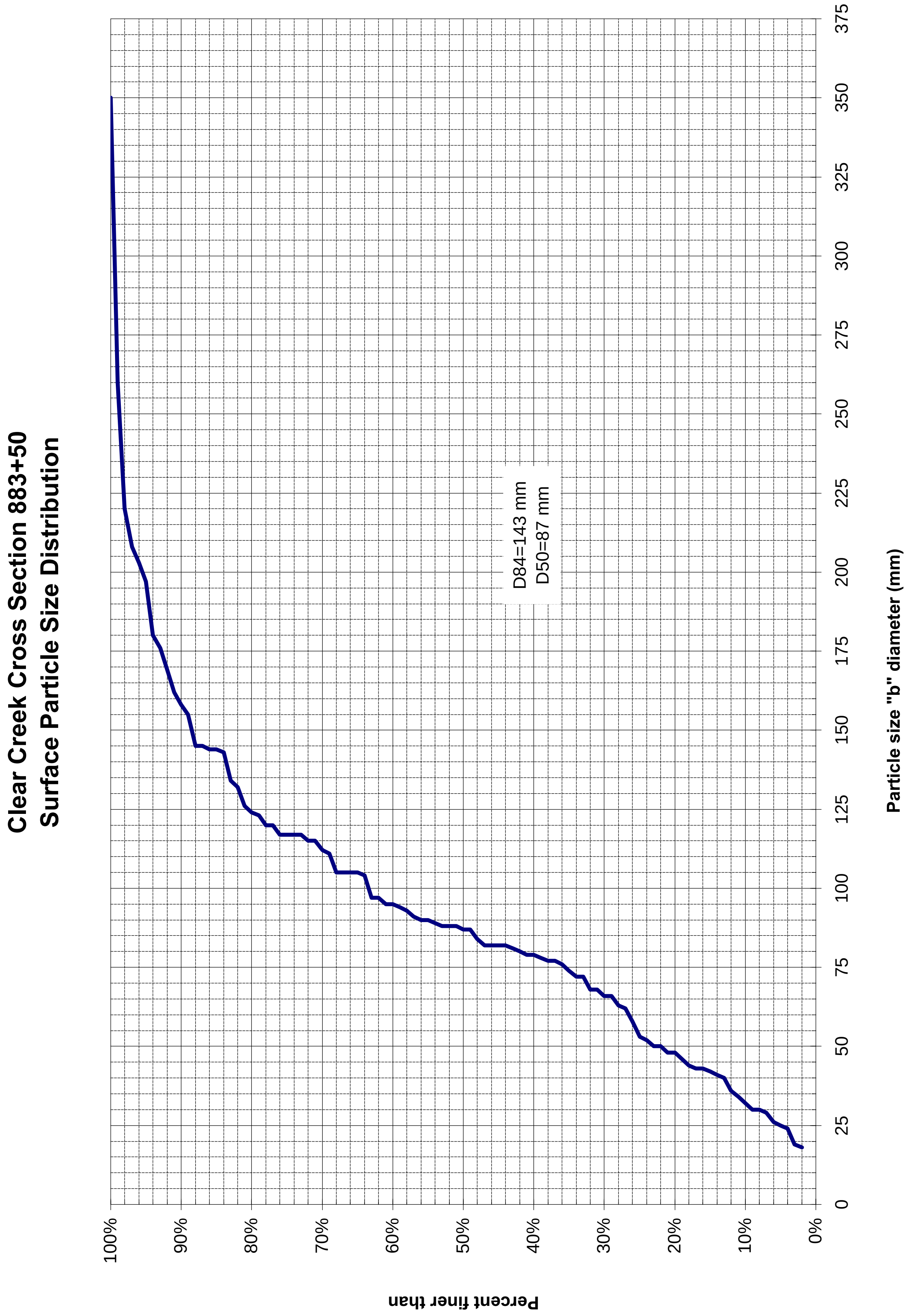
Clear Creek Cross Section 436+25
Surface Particle Size Distribution

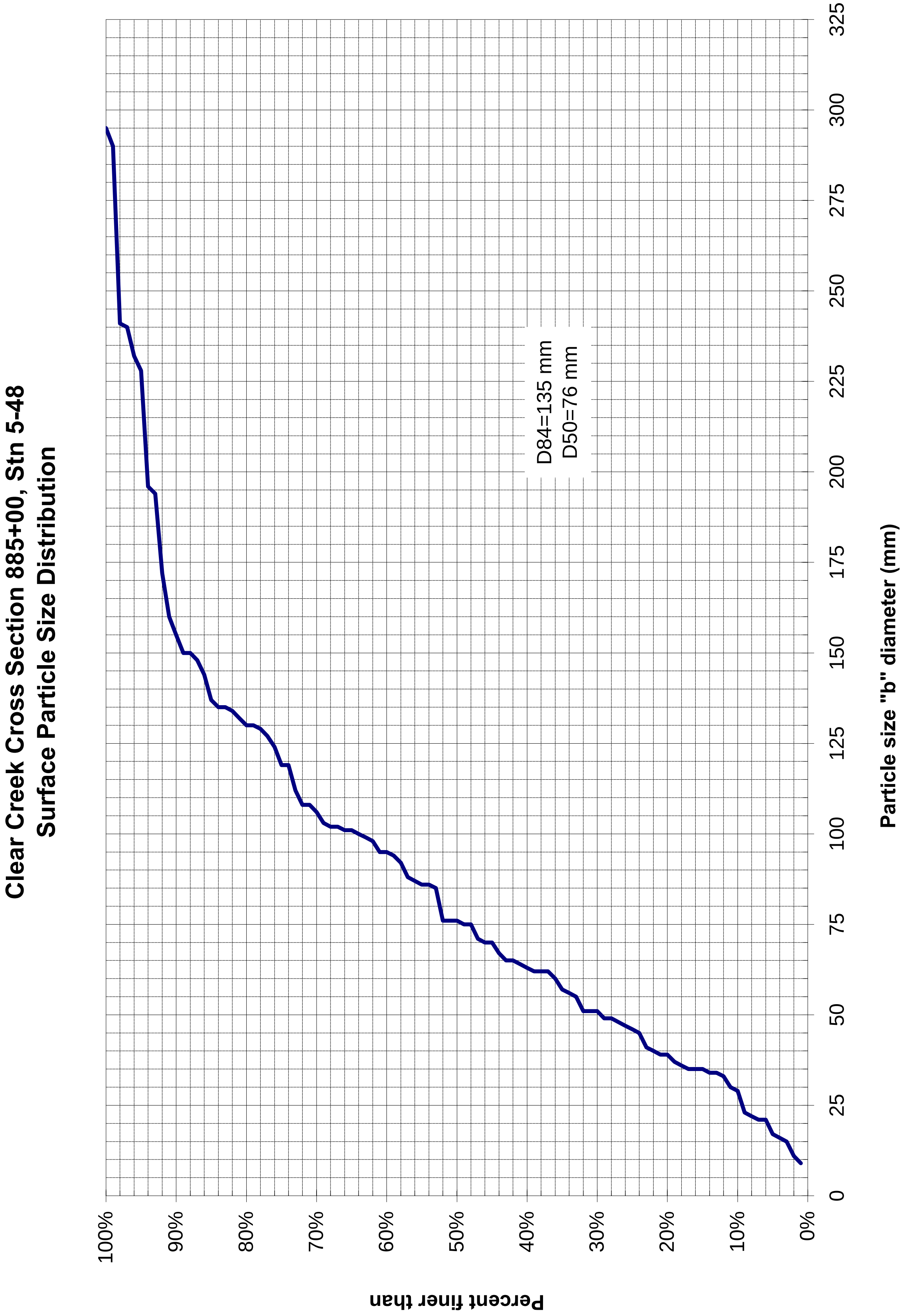


Clear Creek Cross Section 571+10
Surface Particle Size Distribution



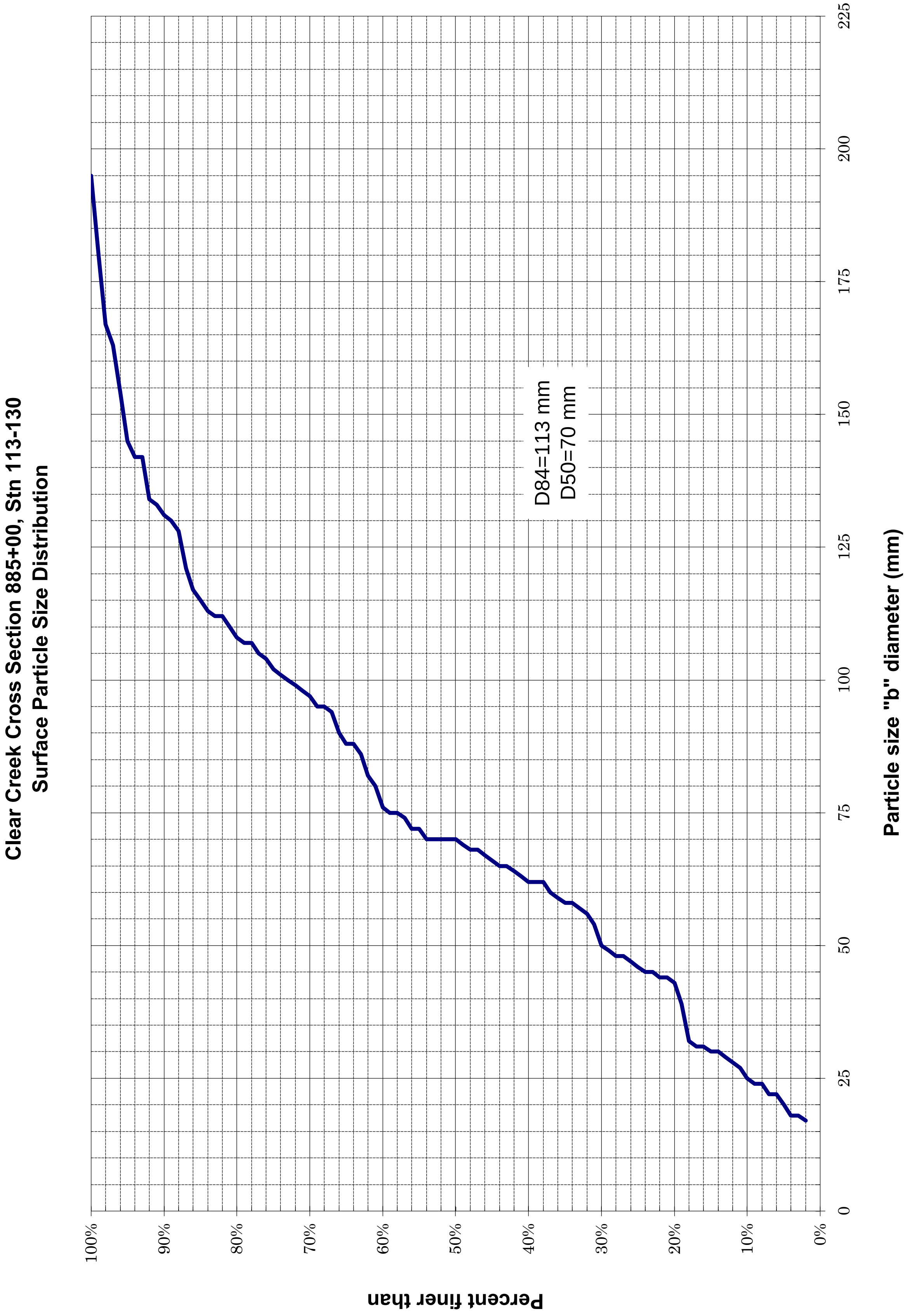
Clear Creek Cross Section 879+00
Surface Particle Size Distribution


Clear Creek Cross Section 883+50
Surface Particle Size Distribution
D84=143 mm
D50=87 mm
Percent finer than
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Particle size "b" diameter (mm)
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375

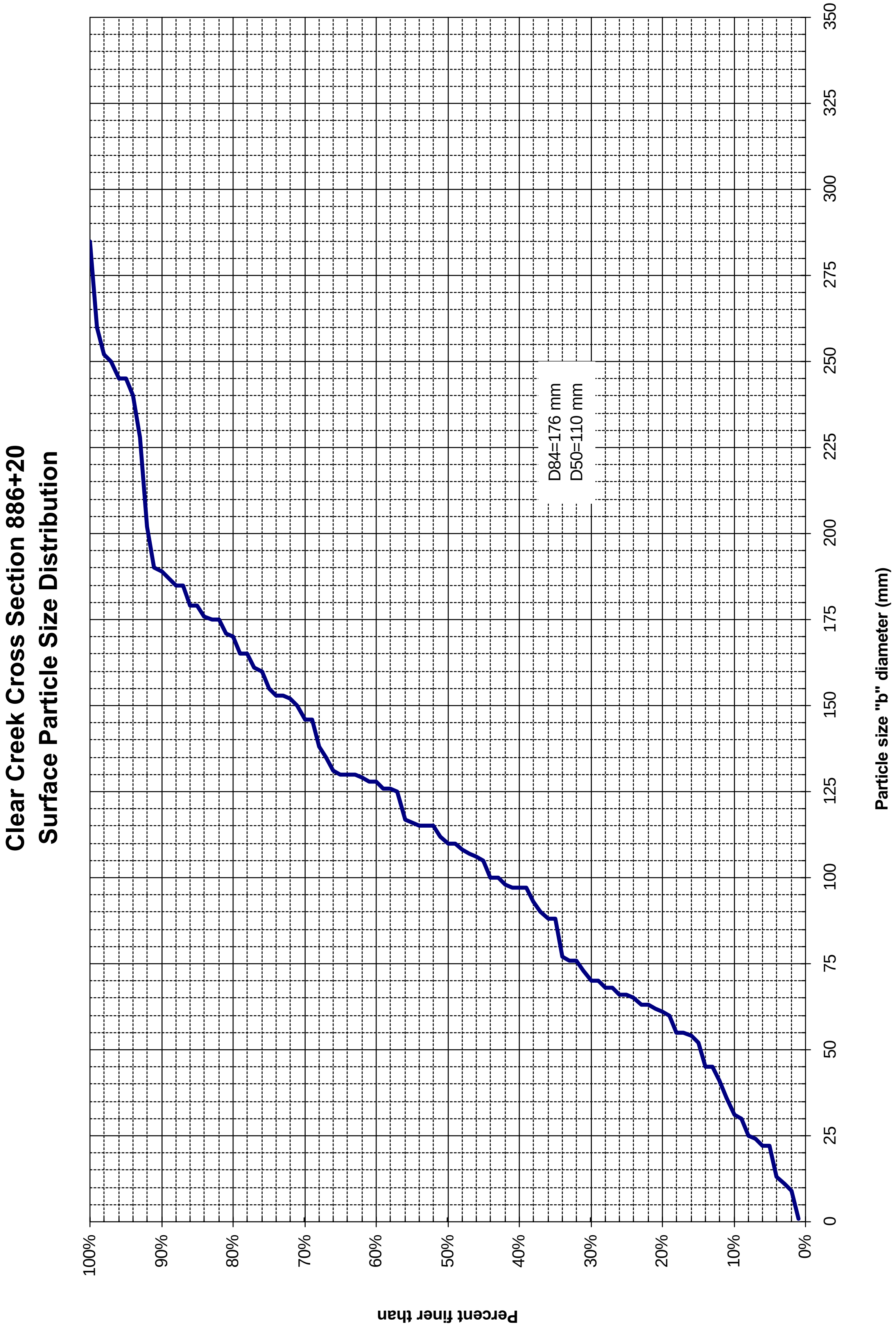


Clear Creek Cross Section 885+00, Stn 5-48
Surface Particle Size Distribution

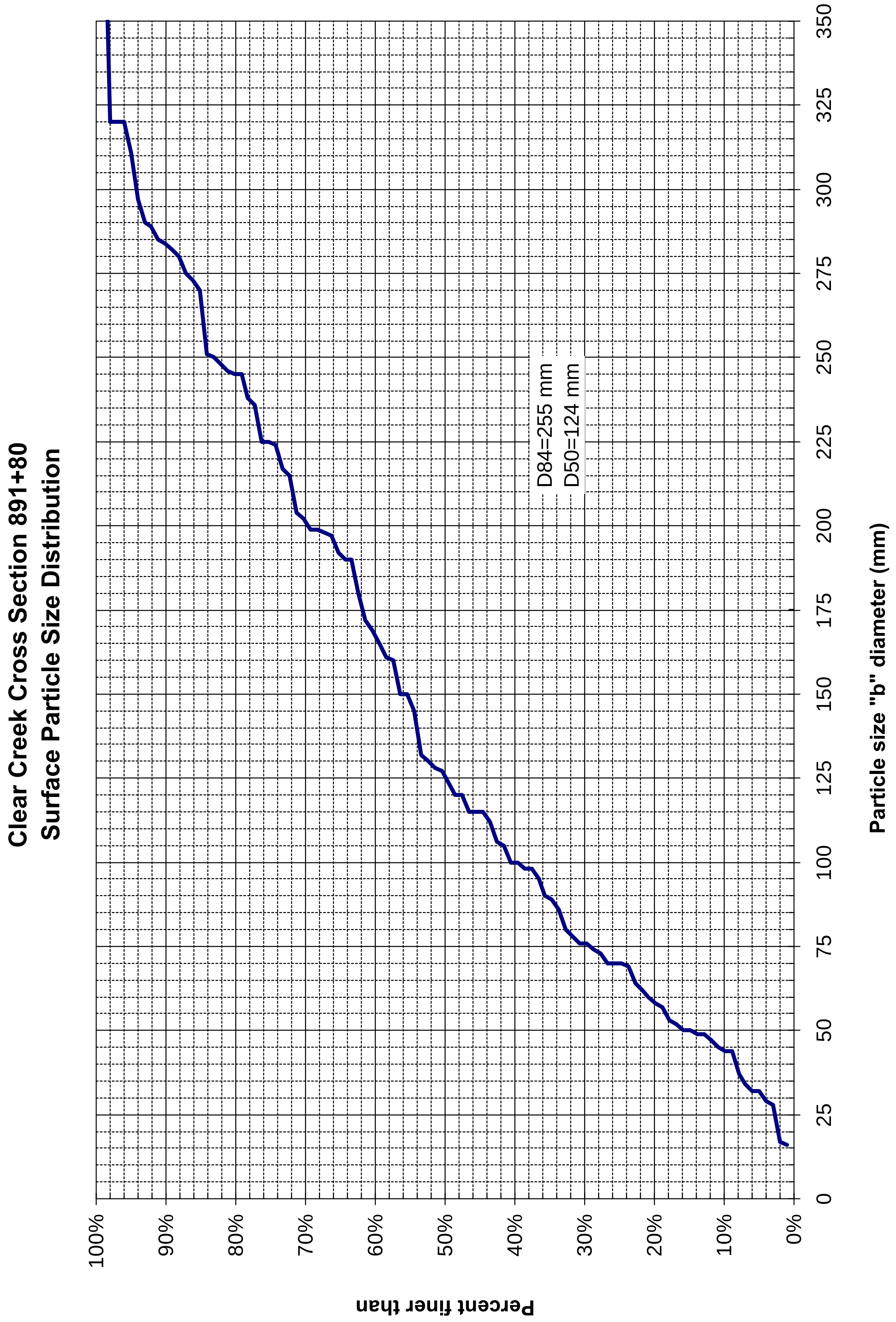
D84=135 mm
D50=76 mm

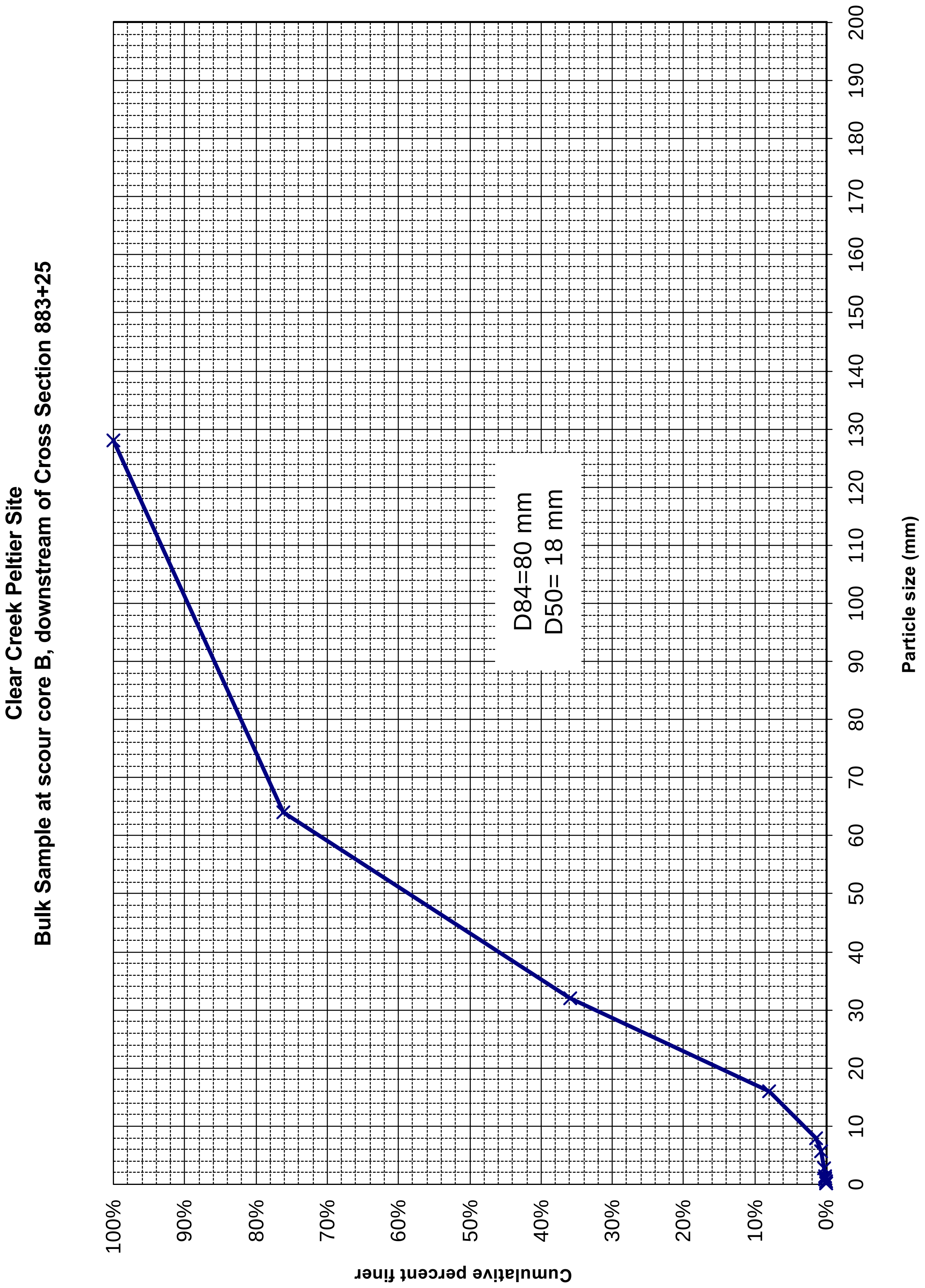


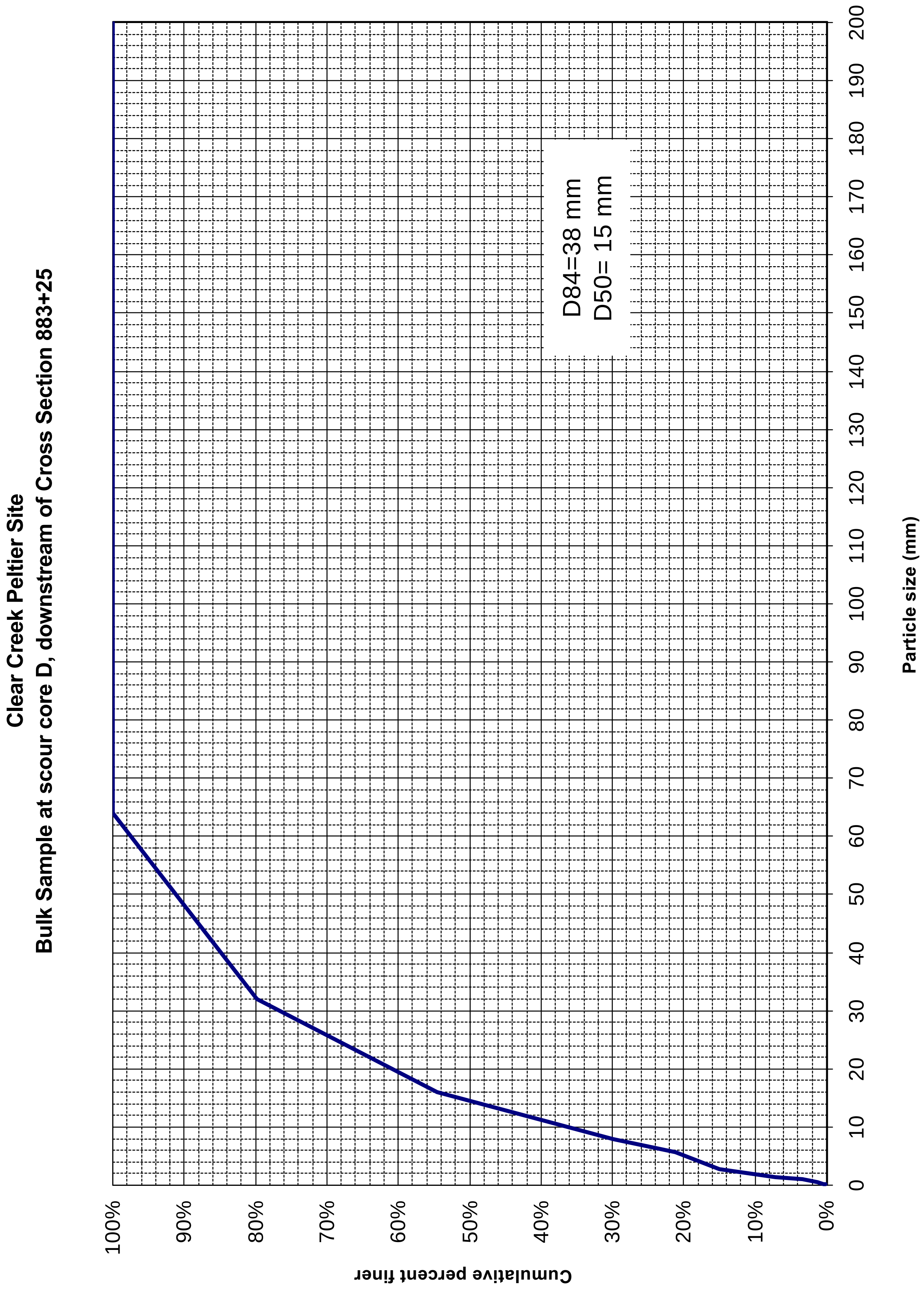
Clear Creek Cross Section 885+00, Stn 113-130
Surface Particle Size Distribution



Clear Creek Cross Section 886+20
Surface Particle Size Distribution

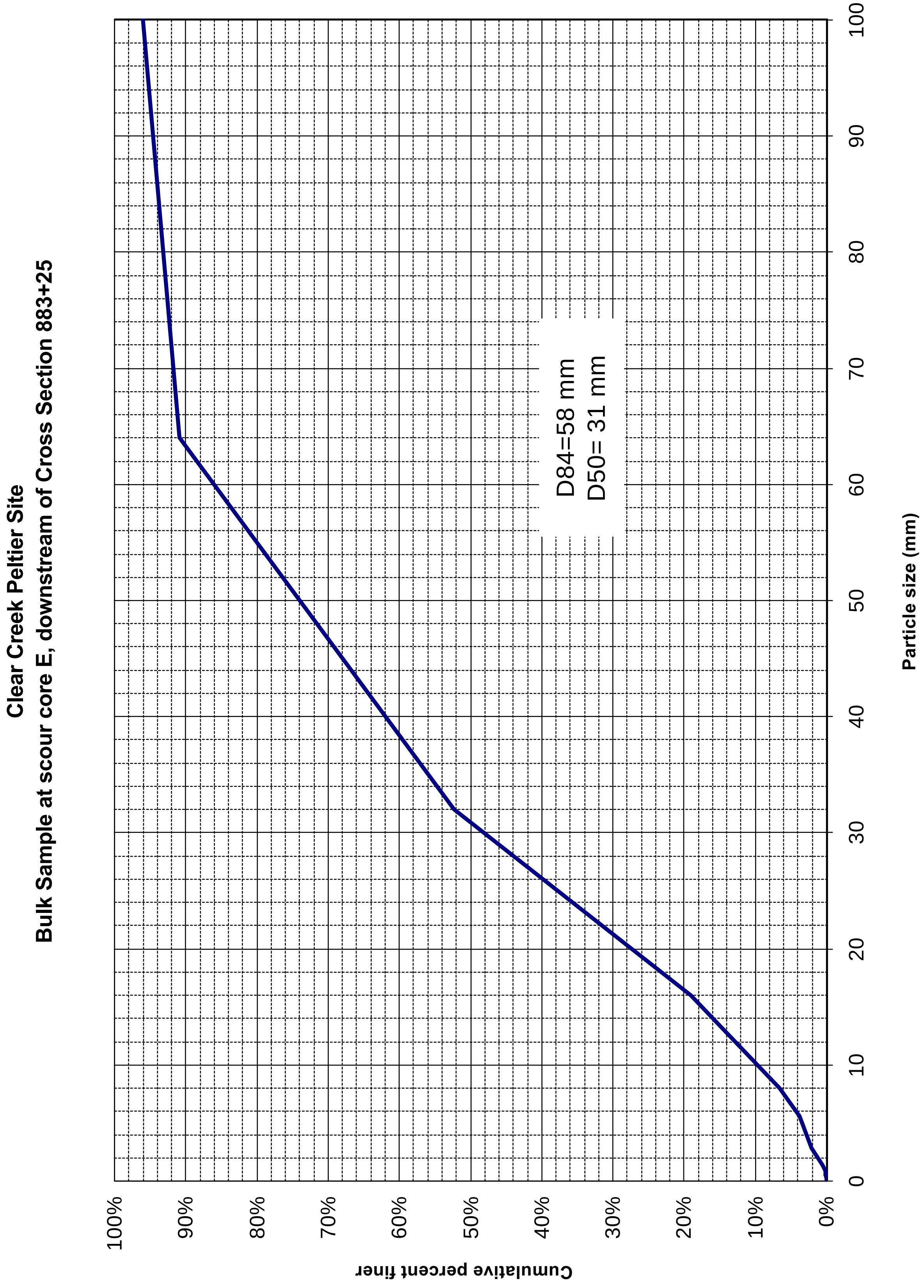

Clear Creek Cross Section 891+80
Surface Particle Size Distribution
D84=255 mm
D50=124 mm
Particle size "b" diameter (mm)
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
Percent finer than
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

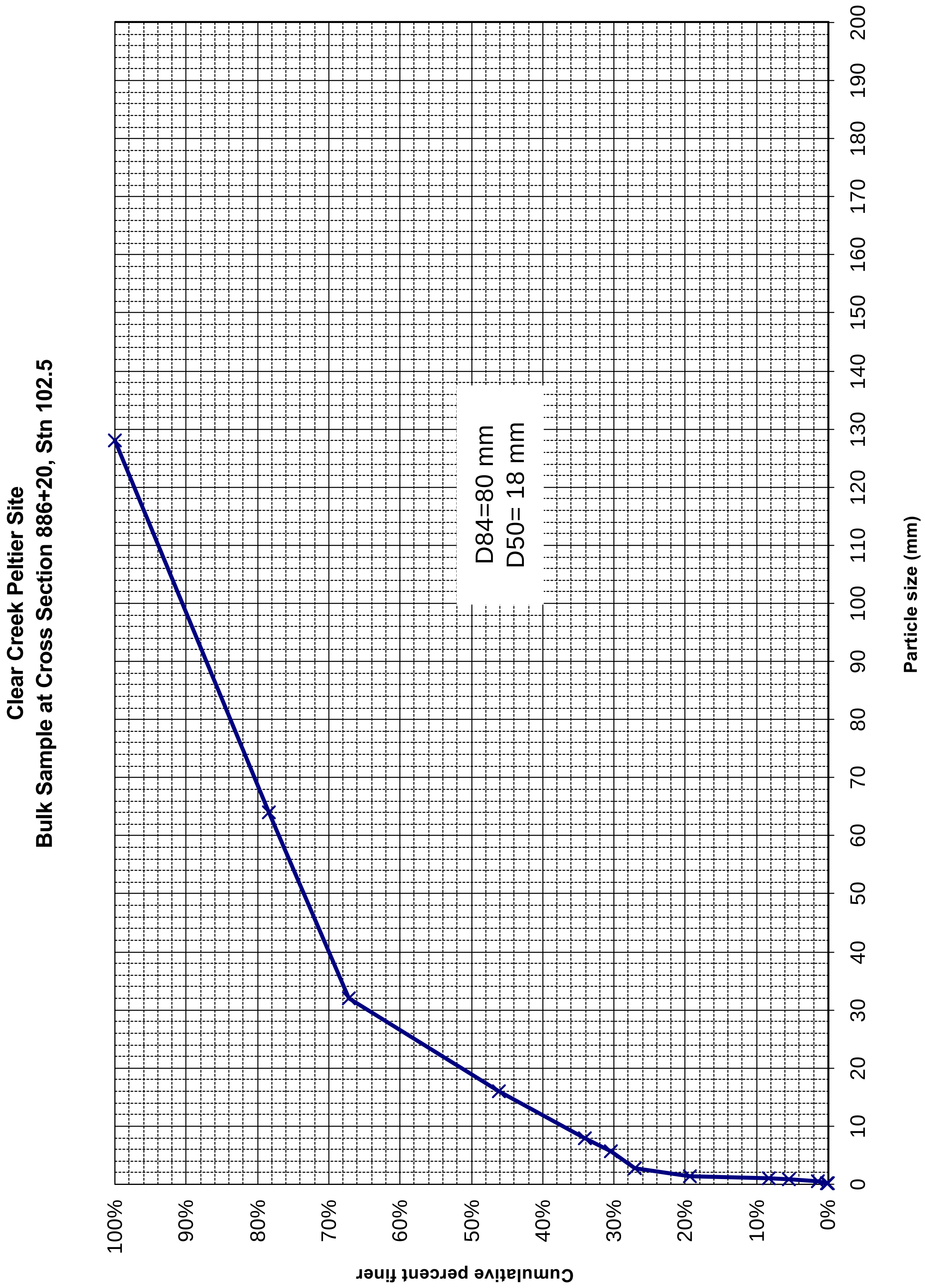

Clear Creek Peltier Site
Bulk Sample at scour core B, downstream of Cross Section 883+25
D84=80 mm
D50= 18 mm
Cumulative percent finer
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Particle size (mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200



Clear Creek Peltier Site

Bulk Sample at scour core D, downstream of Cross Section 883+25


Clear Creek Peltier Site
Bulk Sample at scour core E, downstream of Cross Section 883+25
D84=58 mm
D50= 31 mm
Cumulative percent finer
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Particle size (mm)
0
10
20
30
40
50
60
70
80
90
100



Clear Creek Peltier Site
Bulk Sample at Cross Section 886+20, Stn 102.5

8.4. Appendix D. Lower Clear Creek Gravel Management Plan

APPENDIX D: Lower Clear Creek Gravel Management Plan

FINAL TECHNICAL REPORT
NOVEMBER 2001

PREPARED BY:

McBAIN AND TRUSH
P.O. BOX 663
ARCATA, CA 95518
(707) 826-7794

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1 INTRODUCTION

This Gravel Management Plan for Clear Creek was prepared as an accompanying document to the Clear Creek Geomorphic Evaluation Report. This report contains a review of the current gravel introduction program being implemented by the US Bureau of Reclamation (USBR), the Western Shasta Resource Conservation District (WSRCD), and the Clear Creek Restoration Team, and recommends additional methods to improve coarse sediment storage and spawning gravel conditions in lower Clear Creek below Whiskeytown Dam. The Geomorphic Evaluation Report contains background information describing historical land use activities, the pre and post-dam hydrologic and geomorphic conditions, a geomorphic reach delineation, and monitoring sites and activities. Within this Gravel Management Plan, the reader is referred to Figure 1 for geomorphic reaches, current gravel introduction sites, and study sites.

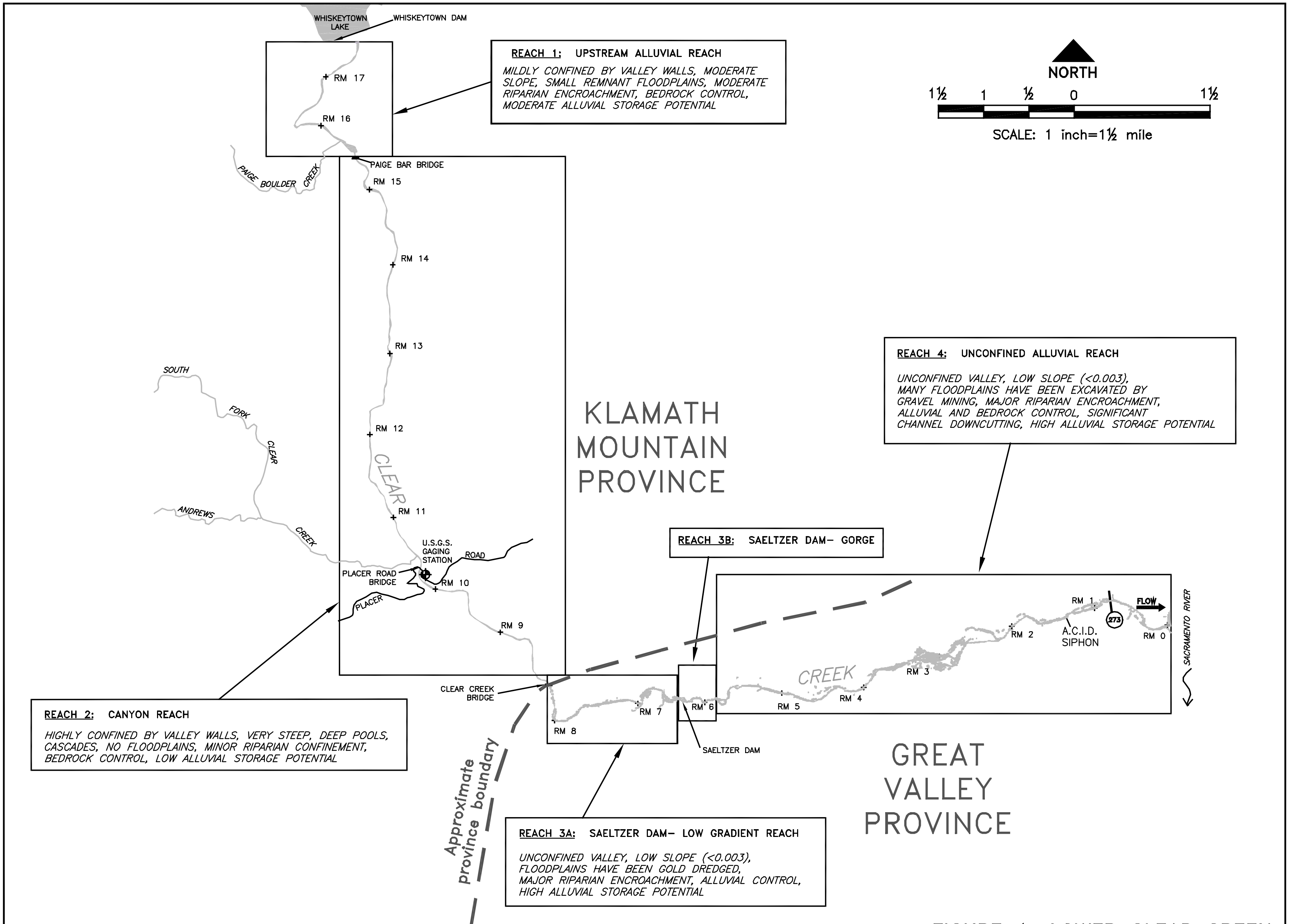
2 SEDIMENT STORAGE CONDITIONS: CONCEPTUAL MODEL

2.1 Description of Unimpaired Conditions

An alluvial river can function naturally only if continuously supplied with sediment. Clear Creek historically transported its sediment load from headwaters and tributary streams downstream to the Sacramento River, forming a continuous link between sediment supply and downstream yield. Coarse and fine sediment budgets were maintained by an approximate balance in sediment inputs (supply), storage, and downstream transport. This dynamic quasi-equilibrium of the sediment budget maintained a natural and healthy channel morphology.

The evolution of coarse sediment conditions in Clear Creek is illustrated in Figure 2. Section “A” of Figure 2 shows conceptual unimpaired conditions and full sediment routing prior to the construction of Whiskeytown Dam. Under these pre-dam conditions, all sediment derived from the upper watershed and tributaries was eventually routed downstream to the Sacramento River. The different geomorphic reaches in Clear Creek had different sloped, widths, and sediment transport capacities, and therefore sediment storage volumes differed within these reaches. This concept is illustrated in the figure by the thickness of the sediment “block”. For example, the 7 mile-long Canyon Reach has higher transport capacity and narrower channel widths, and thus stored a smaller volume of sediment than the downstream alluvial reach. Most importantly, sediment stored as alluvial features such as gravel bars, in pool tails, etc., provided the distinct habitat features utilized by anadromous salmonids.

Section “B” of Figure 2 illustrates coarse sediment conditions resulting from decades of sediment blockage by Whiskeytown Dam, large-scale removal of coarse sediment from the channel from commercial aggregate mining, and alteration in the natural patterns of coarse sediment transport resulting from streamflow regulation. Construction of Whiskeytown Dam in 1963 severely impacted Clear Creek because all coarse sediment transported from the upper Clear Creek watershed is now trapped behind the dam. The lack of sediment supply below the dam, combined with infrequent, large magnitude floods capable of transporting coarse sediment, has resulted in the slow attrition of alluvial storage features (gravel bars, channel bank, channel bed), progressive degradation (downcutting) of the channel, coarsening/armoring of the bed surface, and the steady loss of salmonid habitat. In the Canyon Reach where transport capacity is higher and alluvial sediment storage was historically lower, gravel storage has now been virtually depleted. Only minor tributary inputs from Paige-Boulder Creek and the South Fork of Clear Creek, minor erosion of the channel bed and banks, and from the Clear Creek valley walls, has supplied coarse sediment to the stream. The former Saeltzer Dam may have created a short alluvial reach by trapping coarse sediments upstream of the dam. Downstream in Reach 4 (Figure 2), commercial aggregate mining removed a large volume of sediment, creating a huge “hole” in the alluvial valley that



REACH 1: UPSTREAM ALLUVIAL REACH

MILDLY CONFINED BY VALLEY WALLS, MODERATE SLOPE, SMALL REMNANT FLOODPLAINS, MODERATE RIPARIAN ENCROACHMENT, BEDROCK CONTROL, MODERATE ALLUVIAL STORAGE POTENTIAL

REACH 2: CANYON REACH

HIGHLY CONFINED BY VALLEY WALLS, VERY STEEP, DEEP POOLS, CASCADES, NO FLOODPLAINS, MINOR RIPARIAN CONFINEMENT, BEDROCK CONTROL, LOW ALLUVIAL STORAGE POTENTIAL

REACH 3B: SAELTZER DAM– GORGE

REACH 3A: SAELTZER DAM– LOW GRADIENT REACH

UNCONFINED VALLEY, LOW SLOPE (<0.003), FLOODPLAINS HAVE BEEN GOLD DREDGED, MAJOR RIPARIAN ENCROACHMENT, ALLUVIAL CONTROL, HIGH ALLUVIAL STORAGE POTENTIAL

REACH 4: UNCONFINED ALLUVIAL REACH

UNCONFINED VALLEY, LOW SLOPE (<0.003), MANY FLOODPLAINS HAVE BEEN EXCAVATED BY GRAVEL MINING, MAJOR RIPARIAN ENCROACHMENT, ALLUVIAL AND BEDROCK CONTROL, SIGNIFICANT CHANNEL DOWNCUTTING, HIGH ALLUVIAL STORAGE POTENTIAL

FIGURE 1. LOWER CLEAR CREEK GEOMORPHIC REACHES, KLAMATH MOUNTAIN PROVINCE, AND GREAT VALLEY PROVINCE BOUNDARIES

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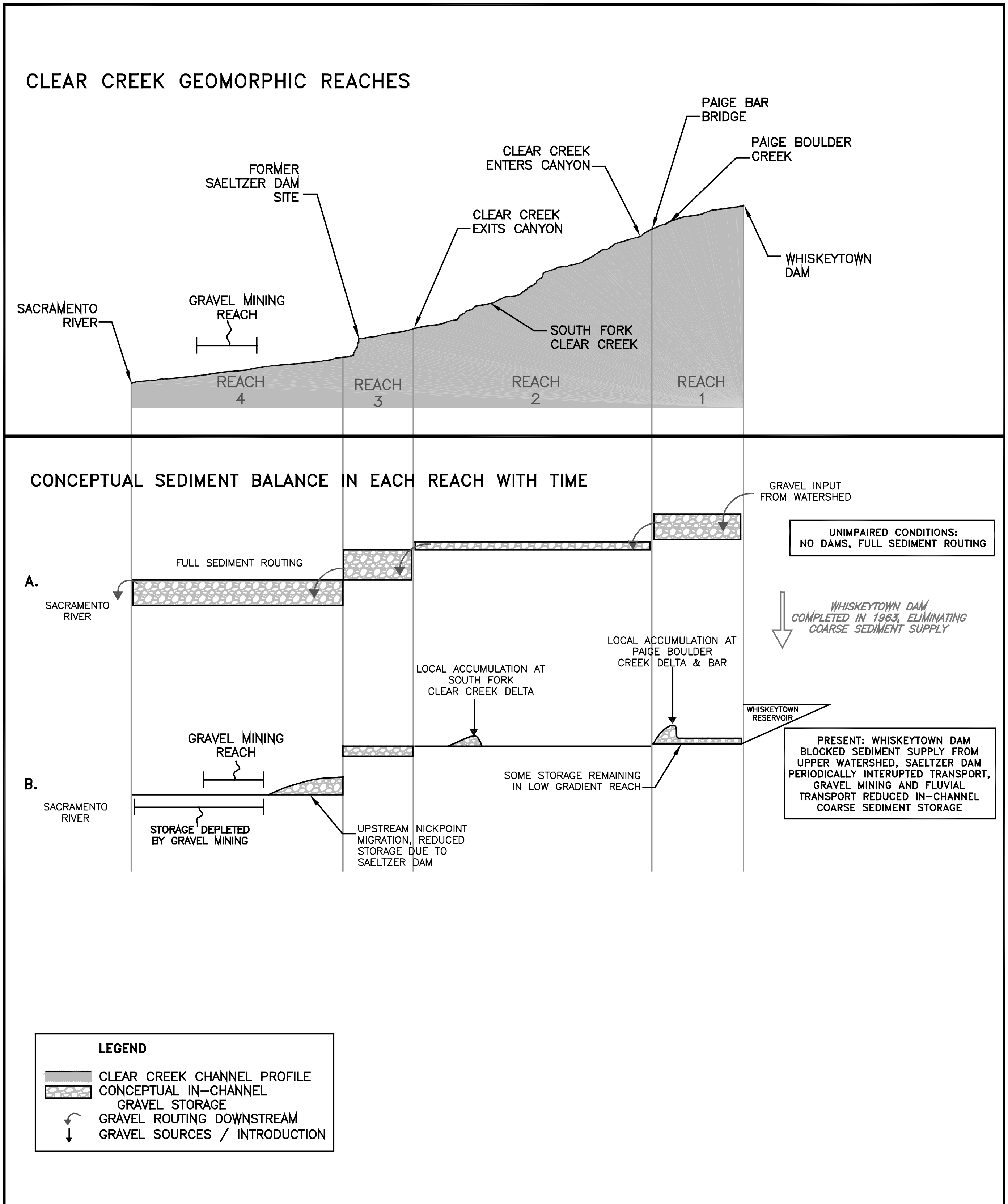


FIGURE 2. LOWER CLEAR CREEK CONCEPTUAL MODEL OF HISTORICAL AND EXISTING COARSE SEDIMENT STORAGE CONDITIONS

12/6/01

would require many decades to fill under current sediment supply conditions. Channel reconstruction in the Floodway Rehabilitation Project will eventually resupply this section of reach by re-filling this hole.

2.2 Historical Surveys

A CDFG survey of salmonid spawning habitat was conducted from Whiskeytown Dam to Saeltzer Dam in 1971 (Coots 1971), and provides some information to substantiate this conceptual model and the evolution of coarse sediment conditions in lower Clear Creek. The survey quantified spawning habitat upstream of Saeltzer Dam, and compared results to a 1956 USFWS and CDFG joint survey conducted prior to the construction of Whiskeytown Dam. The 1971 CDFG memorandum concluded that since construction of Whiskeytown Dam, salmon spawning potential of Clear Creek had "deteriorated significantly". The 1956 survey quantified 347,288 ft^2 of spawning habitat, compared to only 29,121 ft^2 of usable habitat in 1971, a 91% reduction in available spawning habitat. The memo reported that:

> *"Most of the former classified spawning habitat now consists of stretches of unproductive coarse sand deposits which is due to the reduction of the sediment carrying capacity of the stream coupled with the accelerated erosion and continued sediment delivery by tributary drainages below Whiskeytown Dam. Logging activities in unstable terrain similar to the nearby Grass Valley Creek drainage basin appear to be the major contributor of [decomposed granitic] sediment in Clear Creek" (Coots 1971).*

The particle size distribution from three sediment samples in the CDFG memo (bulk sampling methods unspecified) reported that a large proportion of the particles (approximately 30% on average) were finer than 12.8 mm (0.5 inch), indicating the spawning gravels were probably highly embedded with coarse-grained sand and fine gravel.

Salmon spawning gravels were surveyed again in 1982 as part of a PHABSIM study. Examination of the spawning gravels in 1982 revealed that the percentage of fine sediment (< 1-inch diameter) in spawning gravels had increased substantially, comprising 47 to 68 percent of the spawning beds. None of the spawning gravels sampled in 1982 satisfied CDFG criteria for suitable spawning gravel.

The US Fish and Wildlife Service has recently implemented a monitoring program to evaluate the quality of spawning gravels in lower Clear Creek. In 1997 and 1998, they collected bulk samples using a 12-inch diameter McNeil sampler. Samples were collected from spawning gravels at nine sites, with 4 – 5 bulk samples per site. Samples were sieved wet and each fraction measured by volumetric analysis. Data from two years (81 bulk samples) revealed that spawning gravels in the lower Clear Creek corridor are highly impacted with fine sediment (mostly coarse sand <2mm). On average, approximately 50% and 48% of substrate samples (for 1997 and 1998 data, respectively) were composed of particles finer than 13mm, (outside the range suitable for spawning).

McBain and Trush collected and sieved bulk samples in 1999 from gravel deposits below the Peltier Valley Bridge study site (RM 16.4). A single sample on a pool tail where spawning has been observed showed excellent spawning gravel quality, with only a small proportion of gravels outside the range suitable for chinook salmon (25% substrate finer than 13 mm). Three other samples were more similar to the data reported by USFWS; the percentage of substrate smaller than 13 mm ranged from 40% to 70%.

2.3 McBain and Trush Field Surveys

McBain and Trush conducted a mapping survey in February 2000 from Whiskeytown Dam (RM 17.5) to the Clear Creek Bridge (RM 8.4) to (1) assess the extent of coarse sediment storage and salmonid spawning gravel conditions, and (2) estimate volumes of coarse gravel introduction needed to replenish in-channel storage and spawning habitat. Results from this survey would thus draw a rough picture of current sediment storage conditions in the Clear Creek canyon reaches, and provide an approximation of the gravel introduction needs in the canyon. If gravel supplies can be restored in the Reach 1 and in specific locations within the Reach 2 to rebuild bars and other alluvial features, these reaches could provide substantially improved adult holding and spawning habitat for spring chinook salmon, fall chinook salmon, and winter steelhead. The introduced gravel could also eventually route downstream to the lower alluvial reaches, providing uninterrupted bedload transport continuity from Whiskeytown Dam to the Sacramento River. Our surveys focused on Reaches 1 and 2 primarily because (1) the upstream reaches exhibit more highly depleted coarse sediment storage conditions, compared to Reaches 3 and 4, (2) the canyon reaches possess enormous potential for providing habitat for spring run chinook salmon and winter steelhead, particularly if spawning conditions can be improved, and (3) the Clear Creek Floodway Rehabilitation Project and the current WSRCD/USBR gravel introduction programs are currently focusing considerable attention and restoration dollars in Reaches 3 and 4.

During the mapping survey, the aerial extent of sand, gravel, and cobble facies were drawn on laminated aerial photographs, then digitized on orthorectified aerial photographs. A digitized layer for coarse sediment storage included any depositional patch of gravel or cobble within the bankfull channel. A second layer, functionally a subset of the coarse sediment layer, assessed the aerial extent of suitable chinook salmon spawning gravels, (this survey only assessed spawnable gravel deposits, not the suitability of hydraulic conditions over spawning gravels).

We later conducted an additional mapping survey to assess the location and accessibility of potential gravel introduction sites, and developed volume estimates of gravel needed to replenish in-channel storage in Reaches 1 and 2. This survey focused on the Peltier Valley Bridge site (RM 16.0–16.5), the Paige-Boulder Creek site (RM 15.3–15.5), the Igo Gaging Station site at Placer Road (RM 10.2), and the Reading Bar site upstream of Clear Creek Bridge (RM 8.4). We installed and surveyed 21 cross sections traversing the wetted channel, then developed depth recommendations for introducing spawning gravel needed to restore coarse sediment storage. Cross sections were placed to represent a certain length of channel. The potential volume of gravel introduction needed was then estimated by multiplying the cross sectional area of introduced gravels at the cross section by the length of channel. In this way we obtained discrete volumes of gravel introduction needed along these reaches.

The results of the reconnaissance gravel storage surveys are presented in planform maps in Figures 3A-3C, showing the portion of lower Clear Creek from Whiskeytown Dam to Paige Bar Bridge (Reach 1). Reach 1 was a focal point because of their potential value as salmonid habitat, particularly for spring chinook over-summering and spawning. The approximately 7-mile long Reach 2 from Paige Boulder Bridge (RM 15.3) to Clear Creek Bridge (RM 8.4) contained virtually no coarse sediment storage or spawning habitat, and is not recommended for gravel introduction. We did not prepare maps for this lower portion of Reach 2, as was done for Reach 1. Maps present only riffle and pool habitat units, although more detailed meso-habitat data were collected. The areal extent of alluvial sediment stored in the channel (sand, gravel, cobble, boulder), and the total area of spawning-sized gravel, are shown in Figure 3 and are also presented in Table 1. Finally, potential gravel introduction sites are also shown in Figure 3 and will be discussed in detail below.

Our survey revealed severely sediment-starved conditions below Whiskeytown Dam, and a very limited supply of high quality spawning gravel deposits. The section of Clear Creek from Whiskeytown Dam to Peltier Valley Bridge contained only occasional patches of gravels and cobbles, most notably in lee deposits behind large boulders, in a small side channel, and in the large corner pool at RM 17.0. Most of this material was derived from the plume of spawning gravel added by the WSRCD and USBR below the Dam. The spawning gravels sampled at the Peltier Valley Bridge site were perhaps the two best sites in the 9.1 miles of river surveyed. Overall our survey quantified only 19,000 ft^2 of usable spawning habitat

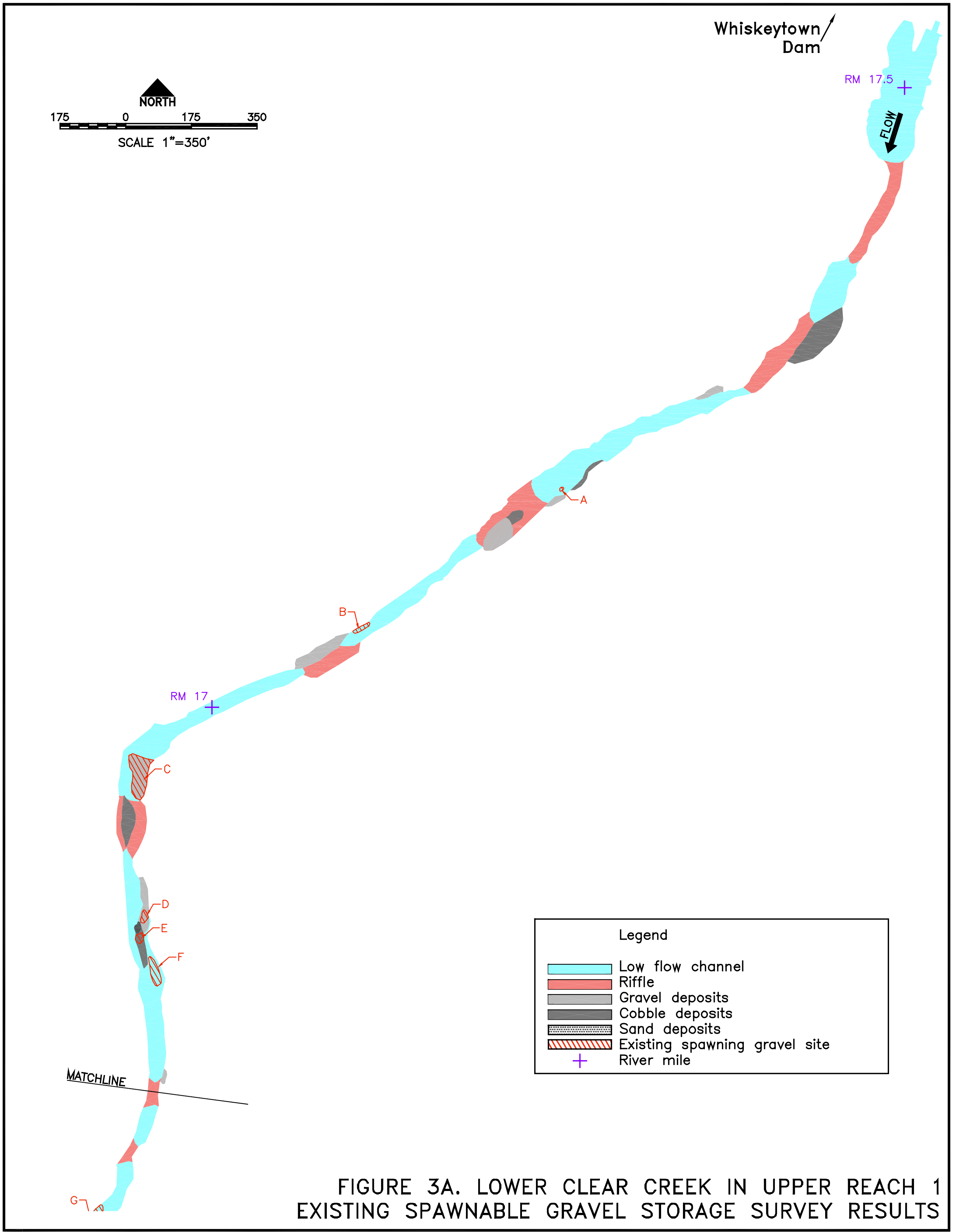


FIGURE 3A. LOWER CLEAR CREEK IN UPPER REACH 1
EXISTING SPAWNABLE GRAVEL STORAGE SURVEY RESULTS

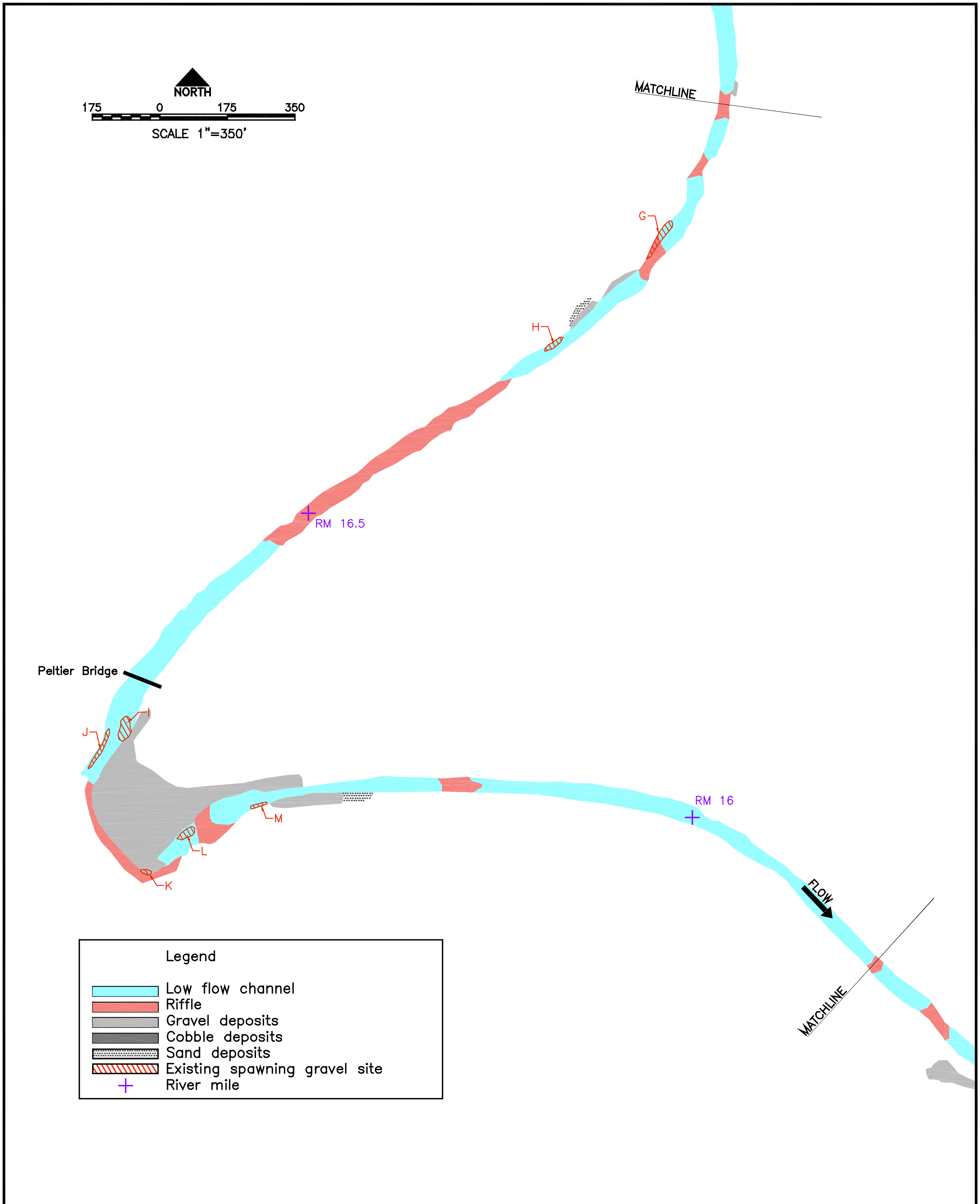


FIGURE 3B. LOWER CLEAR CREEK IN MIDDLE REACH 1
EXISTING SPAWNABLE GRAVEL STORAGE SURVEY RESULTS

12/27/01

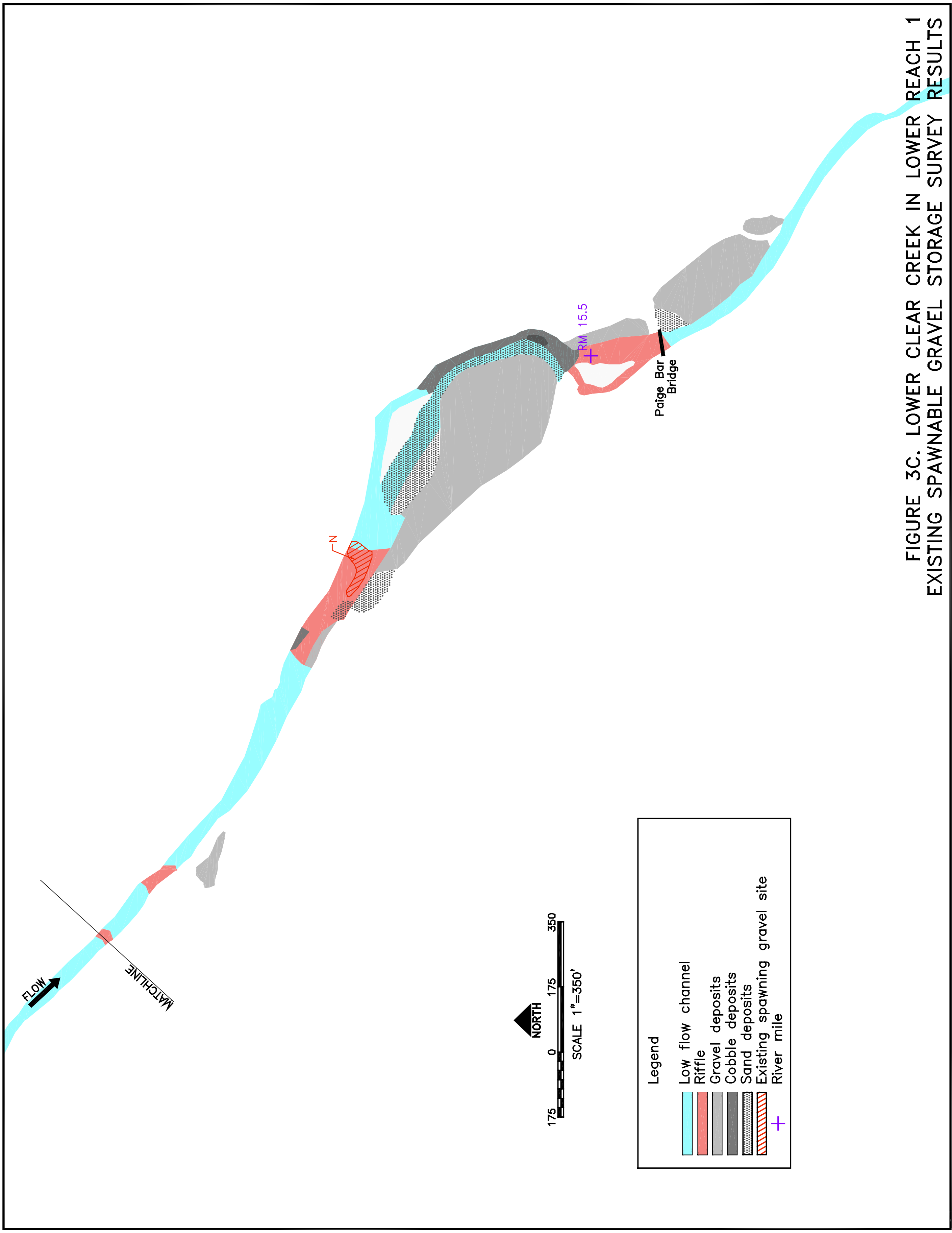


FIGURE 3C. LOWER CLEAR CREEK IN LOWER REACH 1
EXISTING SPAWNABLE GRAVEL STORAGE SURVEY RESULTS

12/27/01

based on gravel suitability (Table 1), a 45% reduction from the Coots 1971 survey. Current spawning habitat availability in the upper two reaches of Clear Creek now represents approximately only 5.5% of the habitat estimated in these same reaches in 1956. As a very crude estimate, this current extent of spawning habitat could support only approximately 88 chinook salmon spawning pairs, based on Burner's (1951) estimate of spawning habitat area requirements of 216 ft^2 per spawning pair.

Table 1. Summary of existing spawning gravel patches mapped in Reach 1 of Clear Creek.

Spawning Gravel patch number from Figure 3	**Area (ft^2)**
A	80
B	470
C	4,780
D	460
E	470
F	1,510
G	1,500
H	635
I	1,500
J	890
K	270
L	820
M	310
N	5,260
TOTAL	**18,955**

3 CURRENT GRAVEL INTRODUCTION METHODS

3.1 Indirect Gravel Introduction [Method 1]

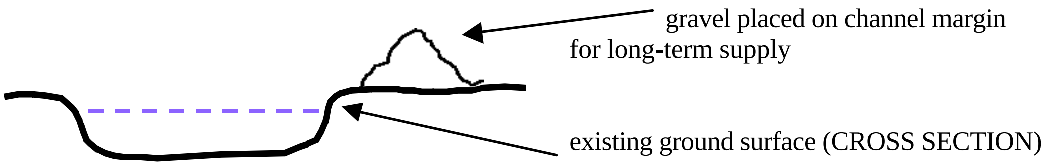
The USBR and the Western Shasta RCD, recognizing the importance of gravel to salmonid habitat, have been implementing gravel introduction for the past several years. One of the methods used is to end-dump gravel approximately 200 ft down the east bank hillslope into the channel below Whiskeytown Dam (Figure 4, Figure 5). A total of 14,000 tons (appx. 9,300 yd^3) of gravel have been placed at this location between January 1998 and June 2001. This method has created a large talus cone down the hillslope and into the channel where gravel is dumped. Additionally, the USBR and WSRCD have added 27,000 tons (appx. 18,000 yd^3) of gravel immediately below the former Saeltzer Dam site since June 1996, and an additional 6,000 tons (appx. 4,000 yd^3) at the Igo Gaging Station below the Old Placer Road Bridge in 2000 using similar methods to those described above.

The primary advantage to this method of gravel introduction is the relatively low cost and easier permitting requirements to implement annual introduction. The largest percentage of costs associated with gravel introduction is the processed gravels and transportation costs. Direct dumping minimizes additional costs, such as additional on-site transportation of gravel once it has been delivered to the introduction site, additional permitting costs for conducting in-channel work, vegetation removal for access, and others.

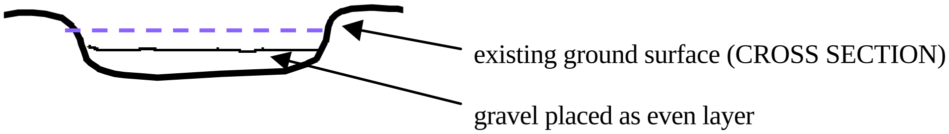
In the reach from Whiskeytown Dam to Peltier Valley Bridge, the coarse sediment inventory revealed small plumes of well-sorted (homogenous) gravels deposited behind boulders and bedrock outcrops, along slow velocity bank areas, in side channels (potentially re-filling degraded scour channels), and in the bottom of pools. Very little gravel had deposited in higher velocity areas such as in pool tails or in

Figure 4. USBR/WSRCD gravel augmentation site directly downstream of Whiskeytown Dam in Lower Clear Creek. This method offers convenience and efficiency, but often requires many years before a spill event distributes gravels downstream to areas that will benefit salmonids.

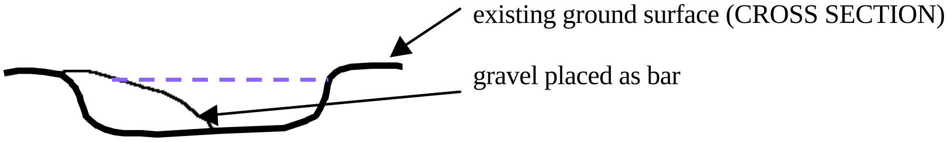
1. METHOD 1: Recruitment pile. This method would place a quantity of gravel on or near the channel margin, available for downstream transport at high flows; long-term recruitment locations could be identified for routine (annual) supplementation; Similar to USBR/WSRCD method;



2. METHOD 2: Riffle supplementation. This method places clean, well-sorted gravel onto the existing channelbed in an even layer of specified depth;



3. METHOD 3A: Point bar supplementation. This method would place gravel as a lateral bar to increase confinement and provide long-term coarse sediment supply;



METHOD 3B: Pool tail supplementation. This method would increase spawning habitat area on overly-steep pool-tails;

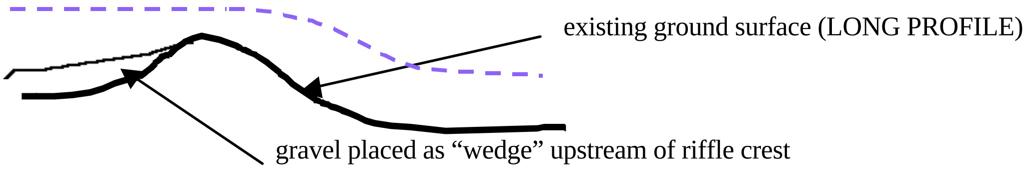


Figure 5. Suggested gravel transfusion and augmentation methods for various sites on lower Clear Creek.

riffles. The introduced gravel had a D_{50} of approximately 60-80 mm, which appeared to be sized to encourage immediate deposition in areas usable for spawning salmonids. At approximately 1,500 ft below Whiskeytown Dam, the homogenously sized introduced gravels had begun to mix with coarser grained cobbles and become incorporated into the bed substrates. Introduced gravels were visible in the channel downstream to approximately 2,500 ft below the dam. A single resident rainbow trout redd was built in a pool tail that had received some deposition of introduced gravels.

The main drawback to this method of introduction is that it is indirect, so that in the absence of controlled high flow releases from Whiskeytown Dam, a lengthy period of time may pass before a spillway flood mobilizes and redeposits introduced gravels downstream (to become available to salmonids). The winter flood regime on Clear Creek has been significantly impaired by regulation from Whiskeytown Dam, such that the 1.5-year recurrence flood was reduced from 5,640 cfs to 2,067 cfs, a 63% reduction in peak discharge. In addition, post-dam daily average flows at the Igo Gaging Station exceeding 2,000 cfs have occurred during only 74 days (in 37 years); flows exceeding 3,000 cfs have occurred in only 36 days in the past 37 years (Figure 6). As presented in the Clear Creek Geomorphic Evaluation Report, flows greater than 2,000 cfs to 3,000 cfs are necessary to mobilize and transport coarse sediment. Additionally, flows exceeding bedload transport thresholds generally occur during events of short duration, followed by long periods (several successive years) in which bedload transport thresholds are not exceeded (Figures 7 and 8). Gravel dumped on the bank may therefore sit immobile for many years before it is transported and redeposited short distances downstream. As Figure 8 indicates, there were many spans of years when threshold-exceeding events did not occur, and one extended period of 13 years (WY 1984 to 1996) during which flows did not exceed 1,000 cfs. Although the direct dumping method provides some benefit in the long-term once it is distributed into the stream by high flows, it often does not maximize the benefits of gravel introduction in the short-term, and may require several years before providing usable salmonid habitat.

3.2 Direct Gravel Placement [Method 2]

A second method of gravel introduction directly places gravel into the channel, raising the bottom of the channel with a 1-3 ft layer of gravels (Figure 5). This method requires some additional effort to transport, deposit, and distribute the gravels within the active and/or bankfull channel along the river corridor, and may require additional permitting hurdles and/or specialized equipment. This method assumes that the river will eventually reshape the gravels into an alluvial morphology (e.g., building alternate bars, riffles, and pools) during infrequent high flow events, and provides the material to do so directly in the channel.

The primary advantage of this method is the direct and timely resupply gravel into the channel for potential immediate use by salmonids. Instead of requiring several years/decades for introduced gravel to route downstream and become incorporated into the channelbed, the channel is initially “restored” in terms of sediment volume with the initial, large sediment “transfusion.” Introduced gravels thus have immediate benefit. A potential additional advantage of this method is that raising and maintaining a higher thalweg elevation would allow high flows more frequent flow access to floodplains (less incised conditions), thereby allowing juvenile salmonid access to important rearing habitat, and allowing floods to scour encroaching riparian vegetation along channel margins. Riparian berms are prevalent throughout most of lower Clear Creek, and cause further channel confinement and consequent downcutting, and isolation of floodplains. The risk of oversupplying the channel by importing too much coarse sediment is minimal because excess sediment would likely become deposited onto bars or floodplains in “storage” for future recruitment. The lack of human infrastructure on Clear Creek minimizes most risks from increased local overbank flows.

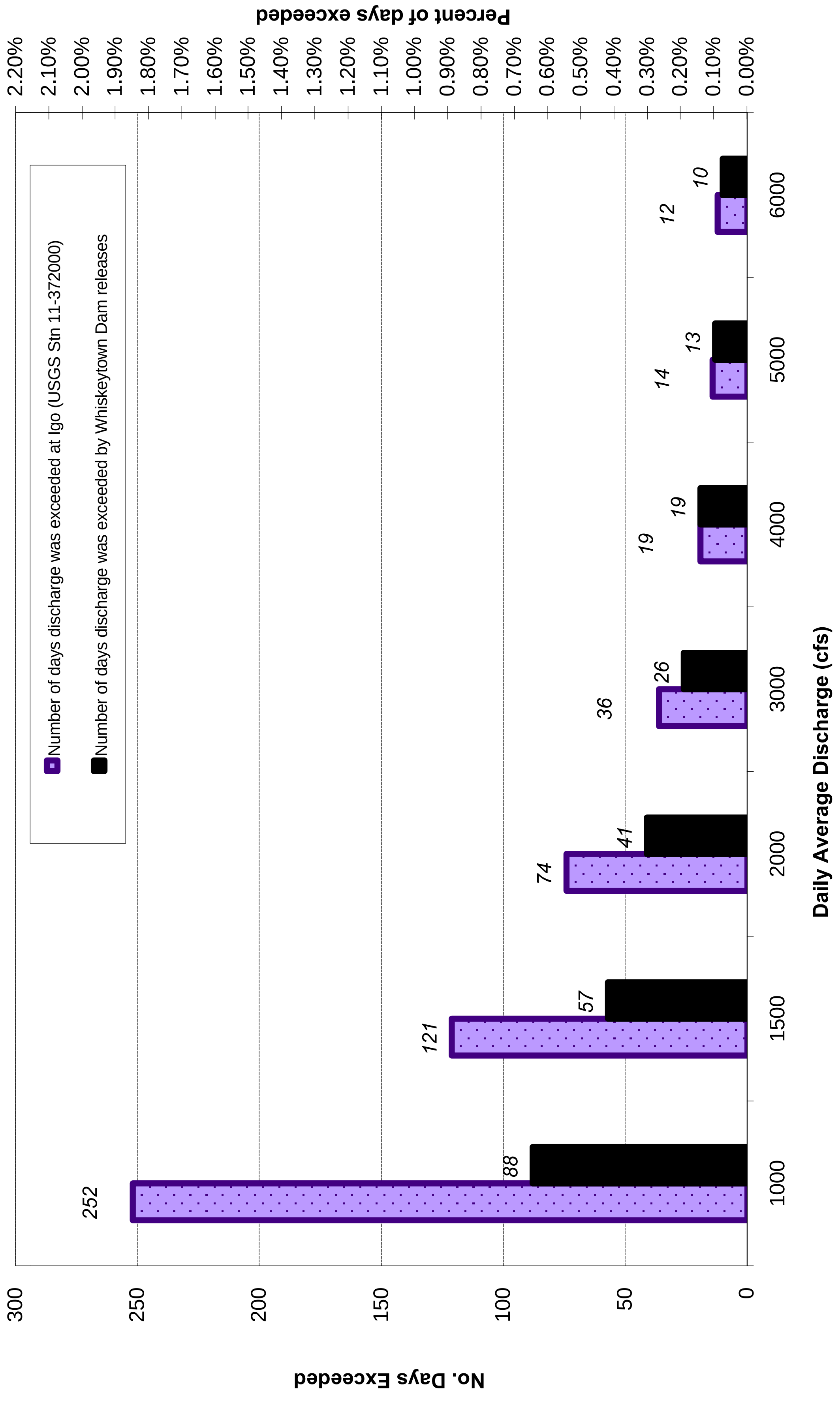


Figure 6. Number of Days Daily Average Discharge on Clear Creek Exceeded Specified Discharges During 35-Year Post-Whiskeytown Era. (WY 1964-99, 12,928 days)

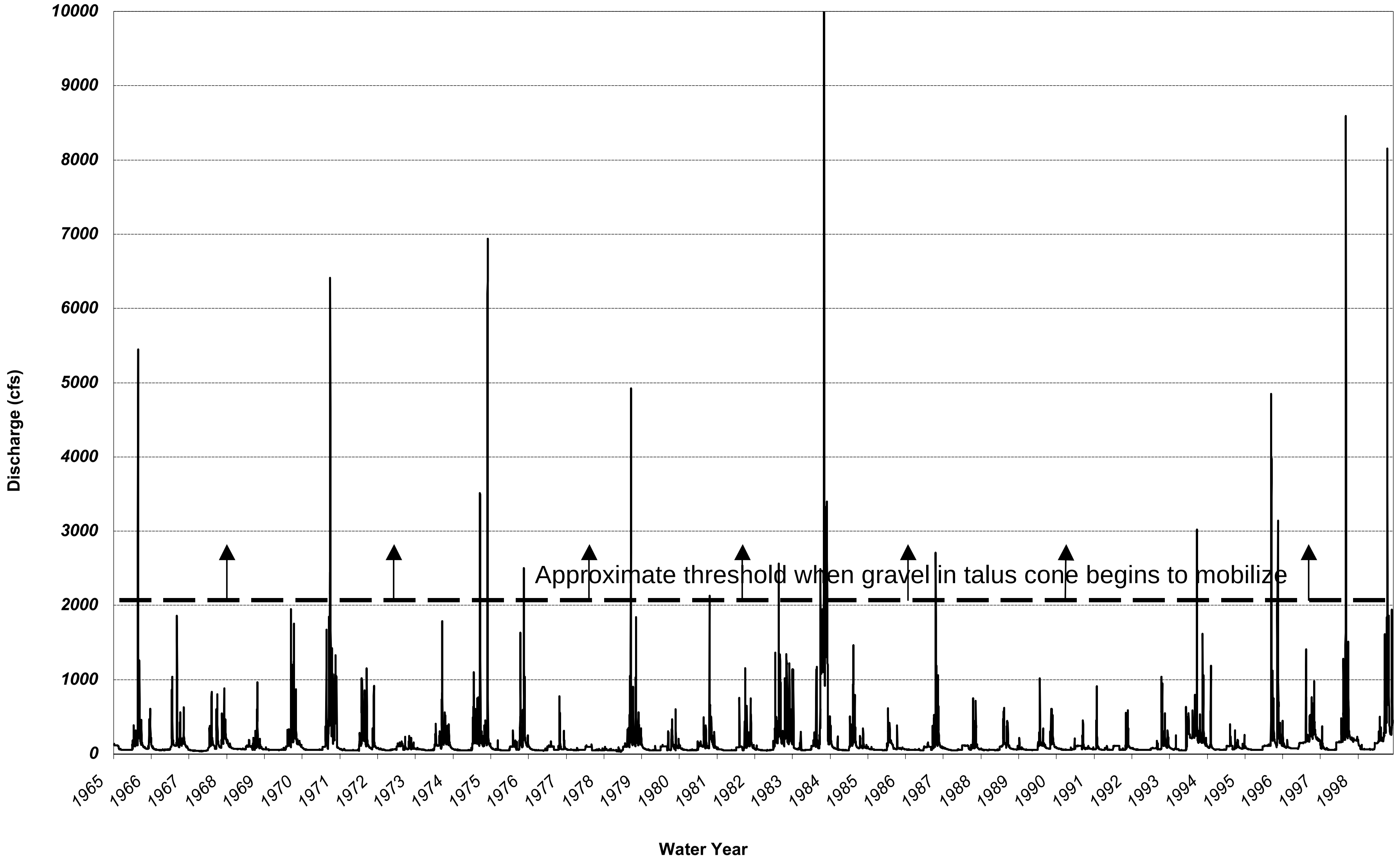


Figure 7. Daily average discharge for Clear Creek near Igo (USGS #11-372000) during the post-Whiskeytown Dam period of Record. Flows exceeding 2,000 cfs to 3,000 cfs are relatively infrequent.

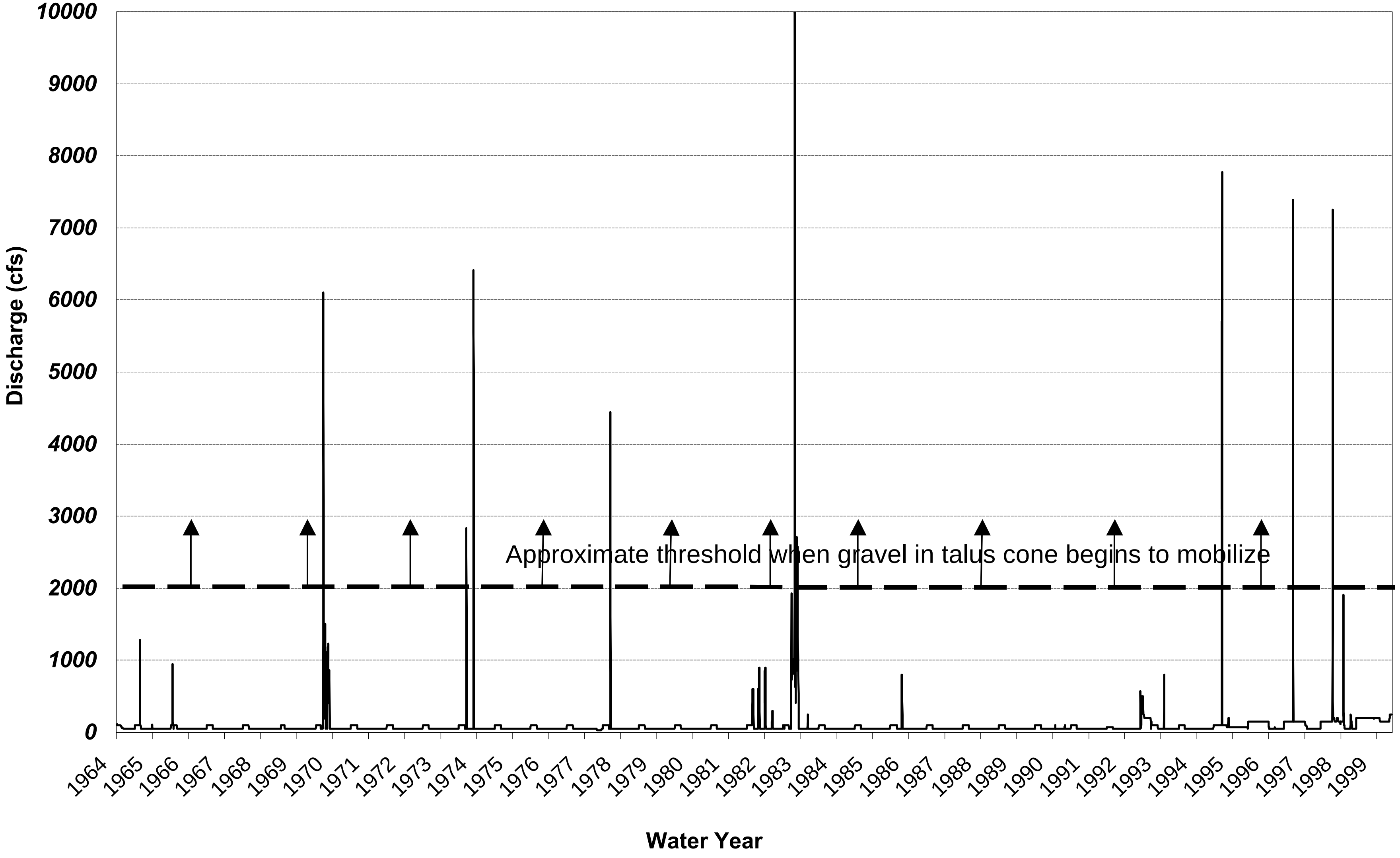


Figure 8. Daily average discharge for Clear Creek at Whiskeytown Dam due to controlled releases and spill events during the post-Whiskeytown Dam period of record.

3.3 Direct Gravel Placement with Contouring [Method 3]

A third method is similar to Method 2, but instead of and/or in addition to placing an even layer of sediment along the channelbed, this method would provide contouring of the introduced gravel (Figure 5). For example, point bars (Method 3A) and pool-tails (Method 3B) would be supplemented or created to mimic natural alluvial features expressed within each site, using low-flow and bankfull channel dimensions developed for the Clear Creek Floodway Rehabilitation Project (McBain and Trush 2000). This method has added benefits over Method 1 and 2 by immediately providing a more natural channel morphology that is usable by salmonids, instead of relying on future high flows to reshape the channel morphology. Additionally, the volume of sediment introduced could be slightly exaggerated (oversupplied) by building gravel bar storage features in order to assure that the targeted “equilibrium” in sediment supply is met without oversupplying or aggrading the channel thalweg. A final benefit is in the aesthetic appearance of the restored channel at gravel introduction sites, which would be designed to resemble a natural alluvial channel. This method, similar to Method 2, would also incur added transportation, field implementation, planning and permitting costs.

4 GRAVEL MANAGEMENT RECOMMENDATIONS

4.1 Recommended Strategy

The overarching approach we recommend for gravel introduction in Clear Creek involves two general steps: first, restoring “equilibrium” sediment storage conditions by a large initial “transfusion” of gravel, placed directly into the channel (Method 2) and in discrete locations as gravel bar storage features (Method 3); and second, maintaining equilibrium sediment conditions through periodic (annual) sediment introduction at specific sites along the corridor using Methods 1, 2, and 3. This approach takes advantage of the benefits of all three gravel introduction methods discussed in the previous section, emphasizing the advantages of each within the overall strategy. This approach also provides immediate benefits by allowing geomorphic processes of bed scour, transport, and redeposition to occur on a more frequent basis, and also by providing high quality salmonid spawning and rearing habitat available for immediate use. Placing the sediment directly into the channel increases the probability that channel-forming flows will be able to mobilize and redeposit gravels as natural alluvial features. Additional finer-grained gravels placed into the channel will also lower thresholds for bed mobility, thus increasing the frequency of bed mobilizing flows.

Our conceptual model illustrates this general strategy of gravel introduction (Figure 9). Beginning with contemporary depleted sediment supply conditions (illustrated in “A” in Figure 9), the proposed gravel introduction strategy is initiated with a large-scale transfusion of gravel at multiple locations to replenish lost storage (illustrated in “B” in Figure 9). This transfusion is proposed for large portions of Reach 1, in Reach 2 below the Igo Gaging Station and upstream of the Clear Creek Bridge, in Reach 3A downstream of the Clear Creek Bridge, continuing the USBR/WSRCD gravel introduction program near the former Saeltzer Dam site in Reach 3B, and in Reach 4 upstream of the Floodway Rehabilitation Project to maintain supply to restored reaches. These locations are described in greater detail below.

With additional gravel supply, the channel can begin reconstructing alluvial features, and redepositing sediment into the bed and banks to reverse decades of channel overwidening and incision. As introduced sediments are distributed downstream (“C” in Figure 9), periodic maintenance of gravel supply will still be required in multiple locations to replace the sediment transported downstream during high flows (“D” in Figure 9). This periodic maintenance would logically occur at the upstream ends of reaches with sediment transport continuity, i.e., the top of the conveyor belt, such as below Whiskeytown Dam and at the Clear Creek Bridge above Reading Bar. Eventually, as illustrated by “E” in Figure 9, gravel transport continuity and alluvial storage capacity would be restored to quasi-equilibrium conditions along the entire Clear Creek corridor. Once this restored condition is reached, periodic gravel introduction of volumes

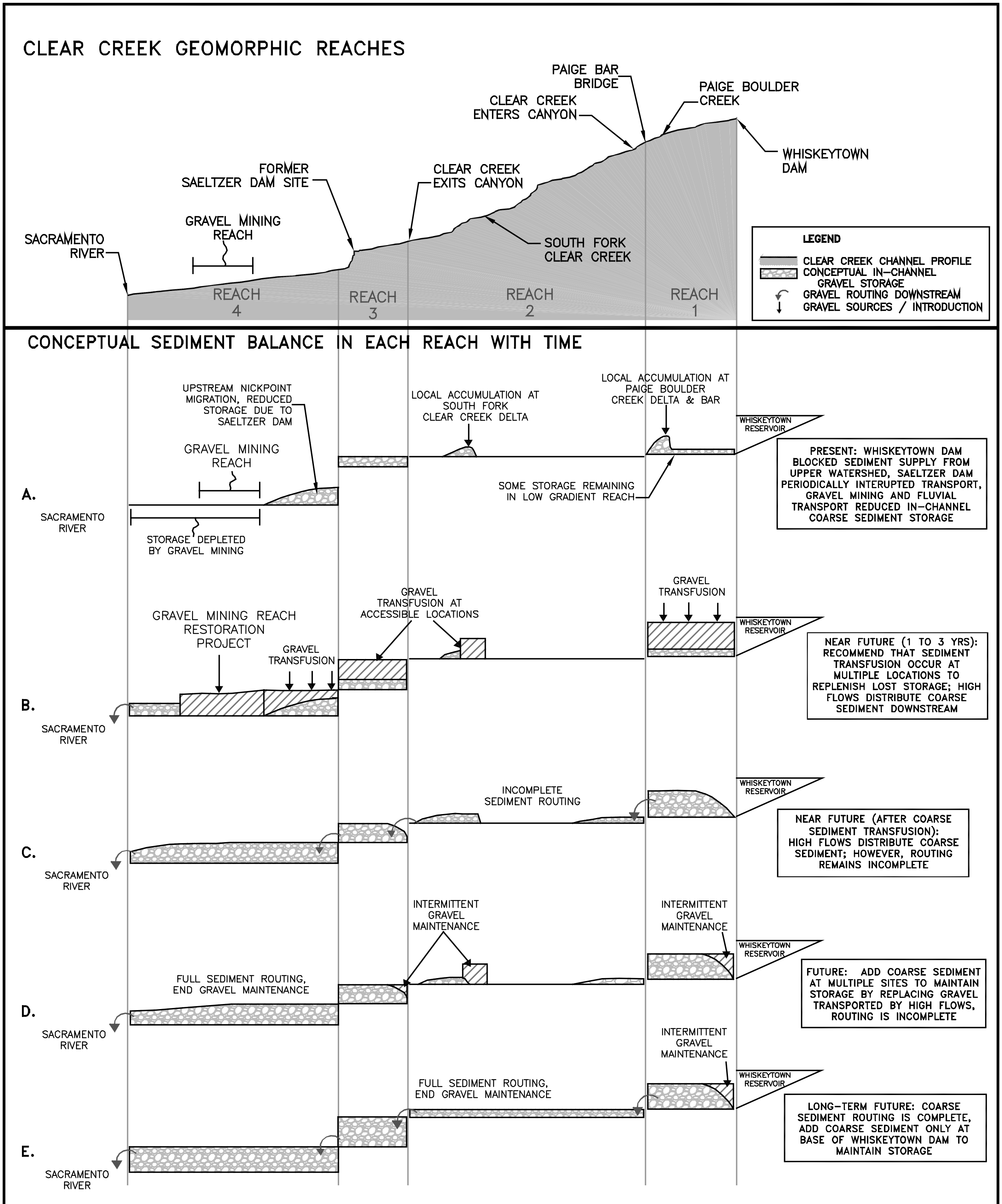


FIGURE 9. LOWER CLEAR CREEK
CONCEPTUAL MODEL OF DESIRED FUTURE
COARSE SEDIMENT STORAGE & ROUTING CONDITIONS

12/21/01

equal to the annual sediment transport rate would be required only at the site immediately below Whiskeytown Dam.

4.2 Short-term supply transfusion

We recommend at least four sub-reaches or sites for short-term gravel transfusion (Figures 10-13). Many of these sites have cross sections to illustrate recommended introduction methods; however, others are simply surface patches and approximate depths, and are located in less accessible areas.

Reach 1. The lower half of Reach 1 is slightly less confined than the upper half of this reach, and offers an excellent opportunity to restore spawning habitat for spring run chinook salmon and winter run steelhead. Haul truck and front-end loader access is possible from Peltier Valley Bridge for approximately 1,000 ft upstream along the left bank (looking downstream), and downstream of the bridge from the left bank for approximately 1,000 ft, and crossing Clear Creek to the right bank to access an additional 900 ft down to where a large right bank bar begins near RM 16 (Figure 10B). Additional access is available upstream from the NEED Camp along the entire right bank to link with sites accessed from Peltier Valley Bridge (Figure 10C). The short-term gravel transfusion in this reach, combined with annual gravel introduction at Whiskeytown Dam (and potentially at Peltier Valley Bridge) will eventually maintain this reach at approximately equilibrium conditions, balancing sediment introduction with downstream transport. Gravel from this reach will eventually route downstream of the Paige-Boulder Bridge, and begin to fill the bedload impedance reach in the canyon below Paige Bar.

As much as 29,000 yd^3 of gravel could be added in Reach 1 as part of the short-term gravel transfusion (Table 2). Gravel should be placed in the channel as discrete point bars along the channel banks and pool tails (Method 3) for polygons 1-8, 9a-d, 10-12, and 15 (Figures 10A, 10B, and 10C). Gravel should also be placed as a constant layer within the entire wetted channel (Method 2) for polygon 9, 13, and 14 (Figures 10B and 10C). Potential introduction morphology at many of the polygons is illustrated on cross section and longitudinal profile plots (Figures 14-28). Several sections within this reach are relatively less accessible and may become lower priority sites. Higher priority sites within this reach would include polygon 9 directly upstream of the Peltier Valley Bridge accessible from the left bank (Figures 14-20), and polygon 14 upstream of Paige-Boulder Creek and accessible from the right bank via the NEED Camp (Figures 27-28). Resupply of gravel in these reaches would greatly benefit spring chinook salmon spawning habitat rehabilitation. The existing low storage conditions and the low slope of the reach would help retain introduced gravels.

Reach 2. Because Reach 2 has very limited access and high transport capacity, few sites are recommended to receive sediment introduction. The life-span of gravels placed in this reach is expected to be relatively low because the canyon has a high transport capacity and low storage potential. Where the valley widens slightly at the Igo Gaging Station, however, alluvial deposits will provide some additional salmonid spawning and rearing habitat. Sediment transfusion combined with annual/periodic introduction will eventually restore equilibrium conditions within the lower canyon reach downstream of Placer Bridge. We recommend placing at least 1,300 yd^3 of gravel as lateral bars and supplementing pool tails as naturally contoured features (Figure 11, Figures 29-30, Table 2).

An additional gravel transfusion site can be accessed from the Clear Creek Bridge and is just upstream of the bridge (Figure 12). Creating a large point bar on the forced meander and supplementing the pool tail will help maintain sediment supply to the lower gradient Reach 3A at Reading Bar where floodplain restoration has occurred. Approximately 2,500 yd^3 of gravel should be placed as a point bar and pool tail supplementation at this site (Figure 12, Figure 31, Table 2).

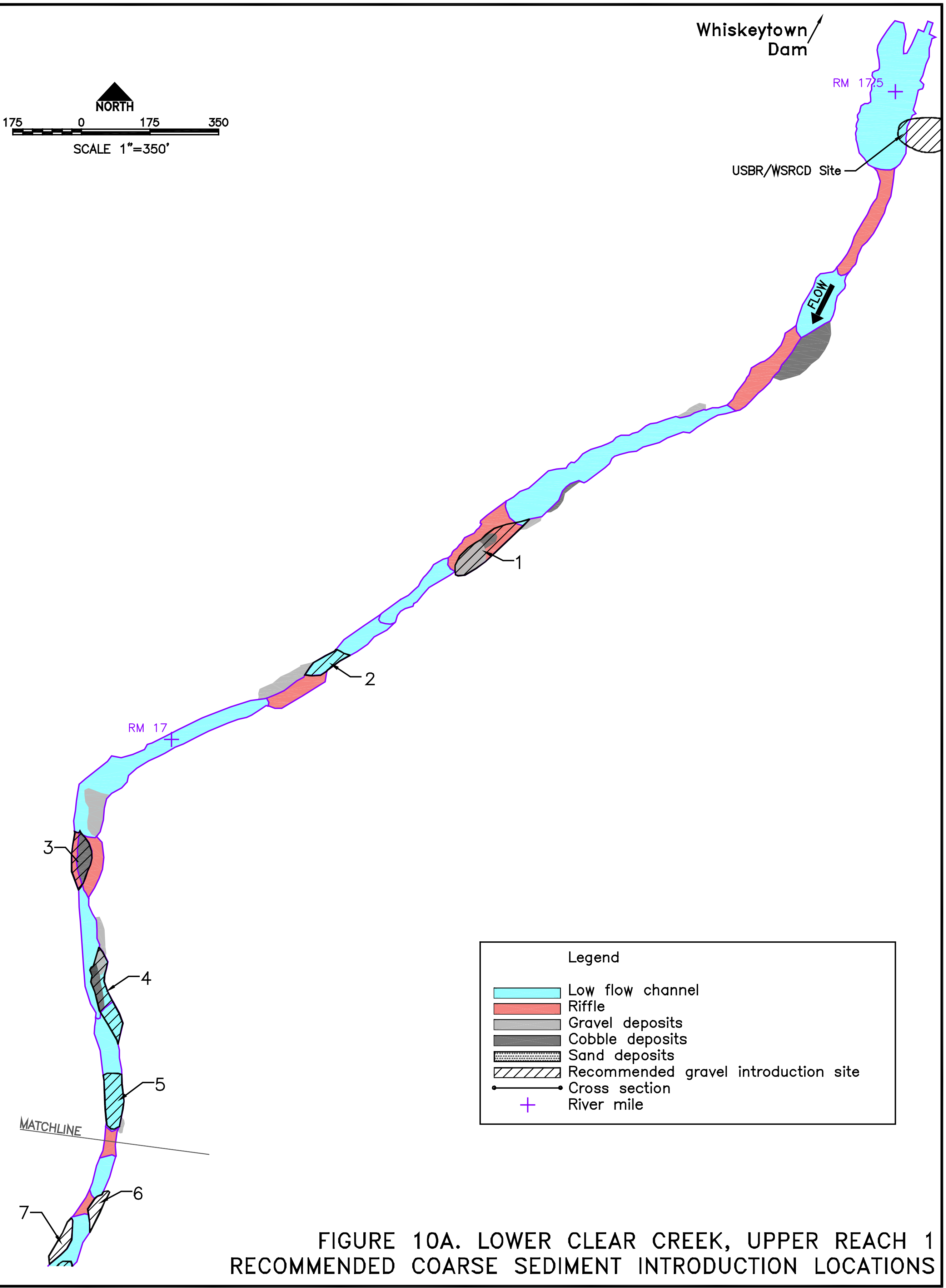


FIGURE 10A. LOWER CLEAR CREEK, UPPER REACH 1
RECOMMENDED COARSE SEDIMENT INTRODUCTION LOCATIONS

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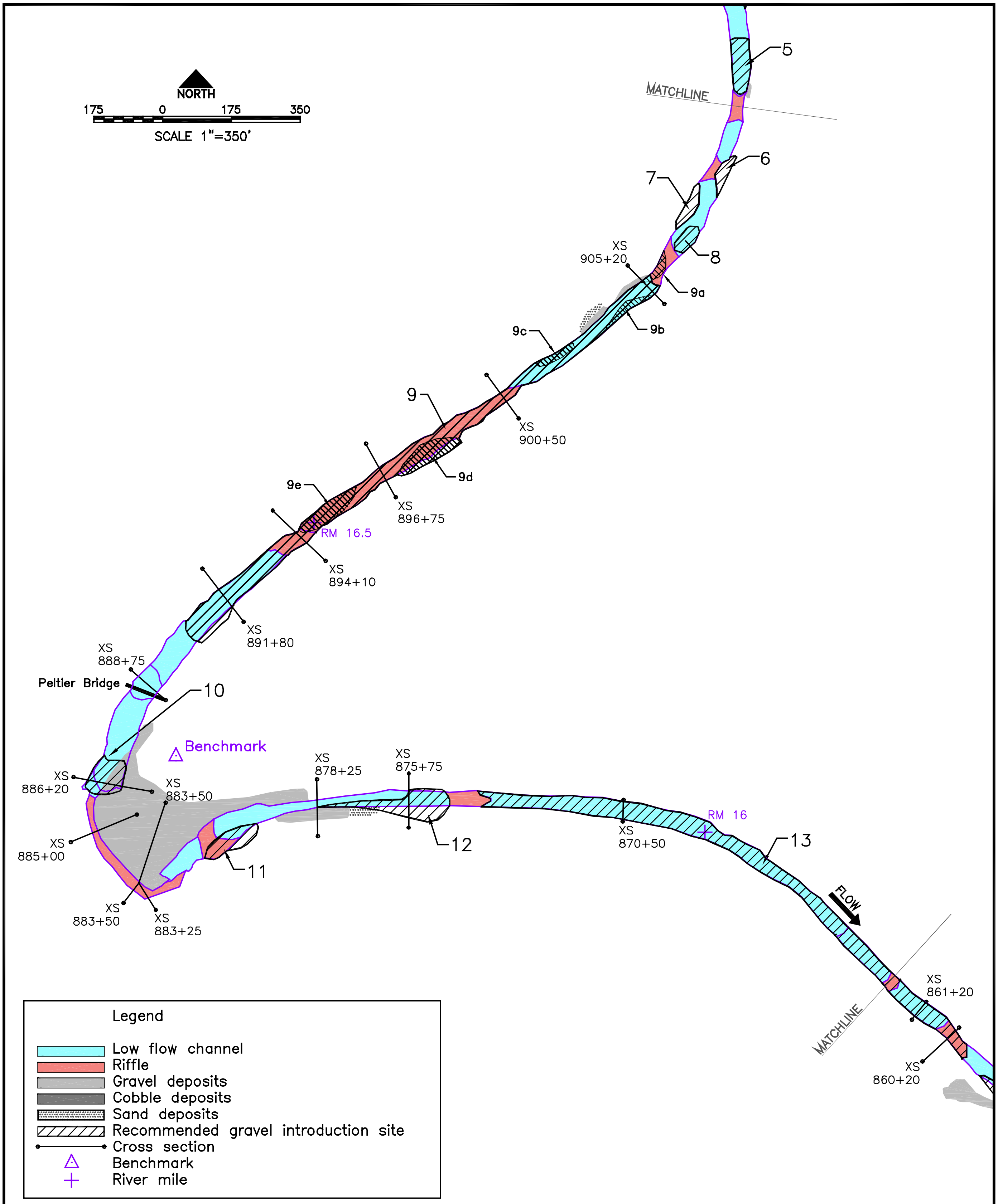

FIGURE 10B. LOWER CLEAR CREEK, MIDDLE REACH 1
RECOMMENDED COARSE SEDIMENT INTRODUCTION LOCATIONS

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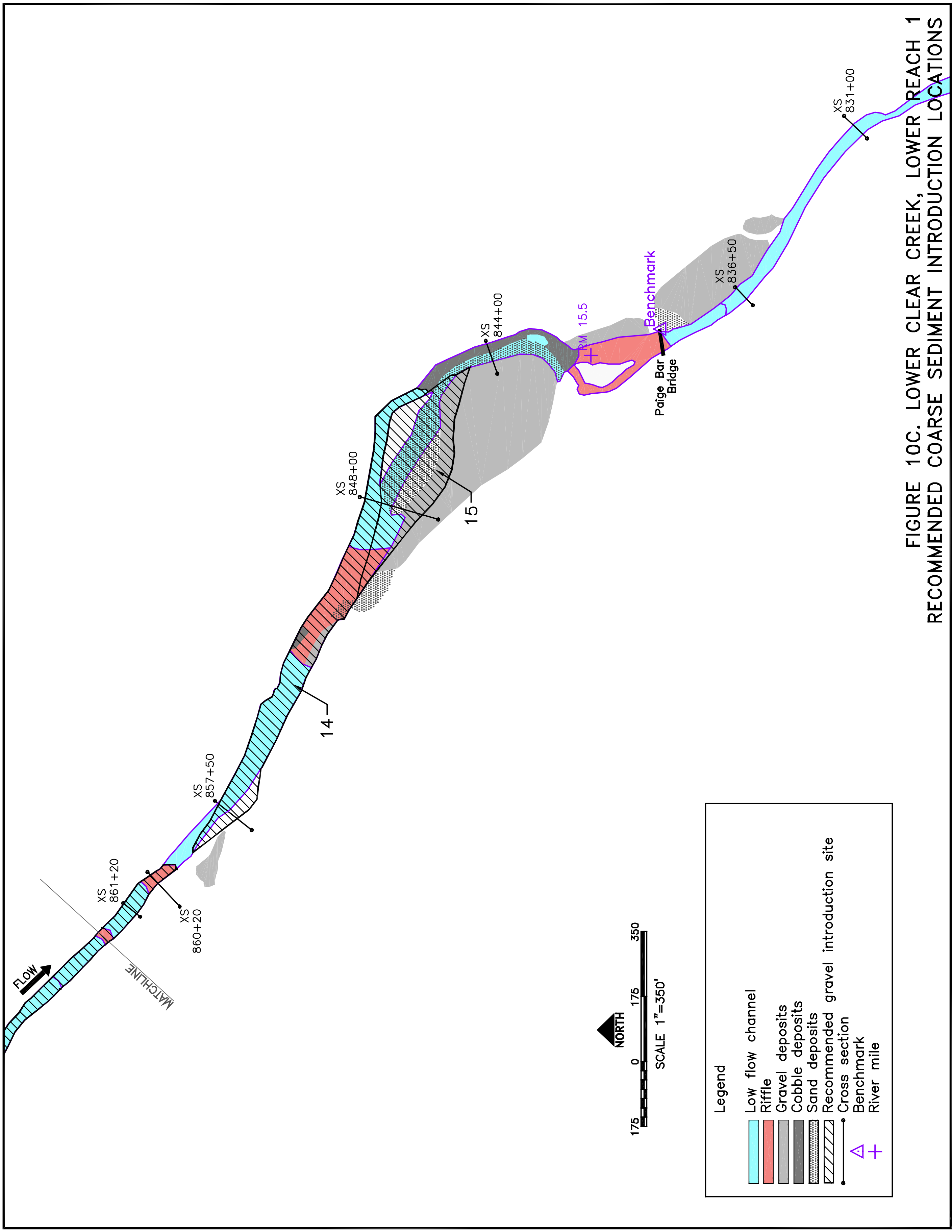

FIGURE 10C. LOWER CLEAR CREEK, LOWER REACH 1
RECOMMENDED COARSE SEDIMENT INTRODUCTION LOCATIONS

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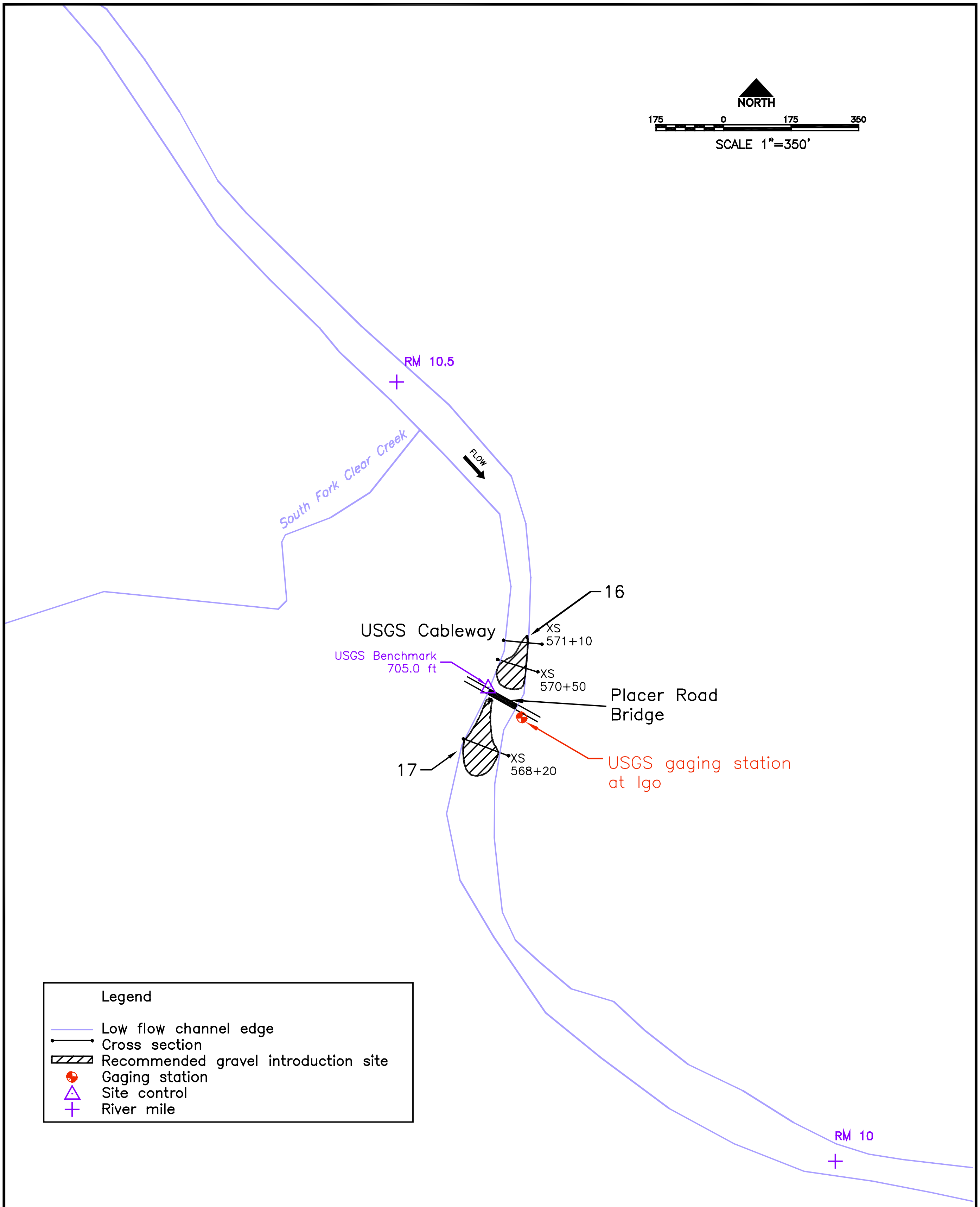

FIGURE 11. LOWER CLEAR CREEK, LOWER REACH 2
IGO GAGING STATION RECOMMENDED COARSE SEDIMENT INTRODUCTION LOCATION

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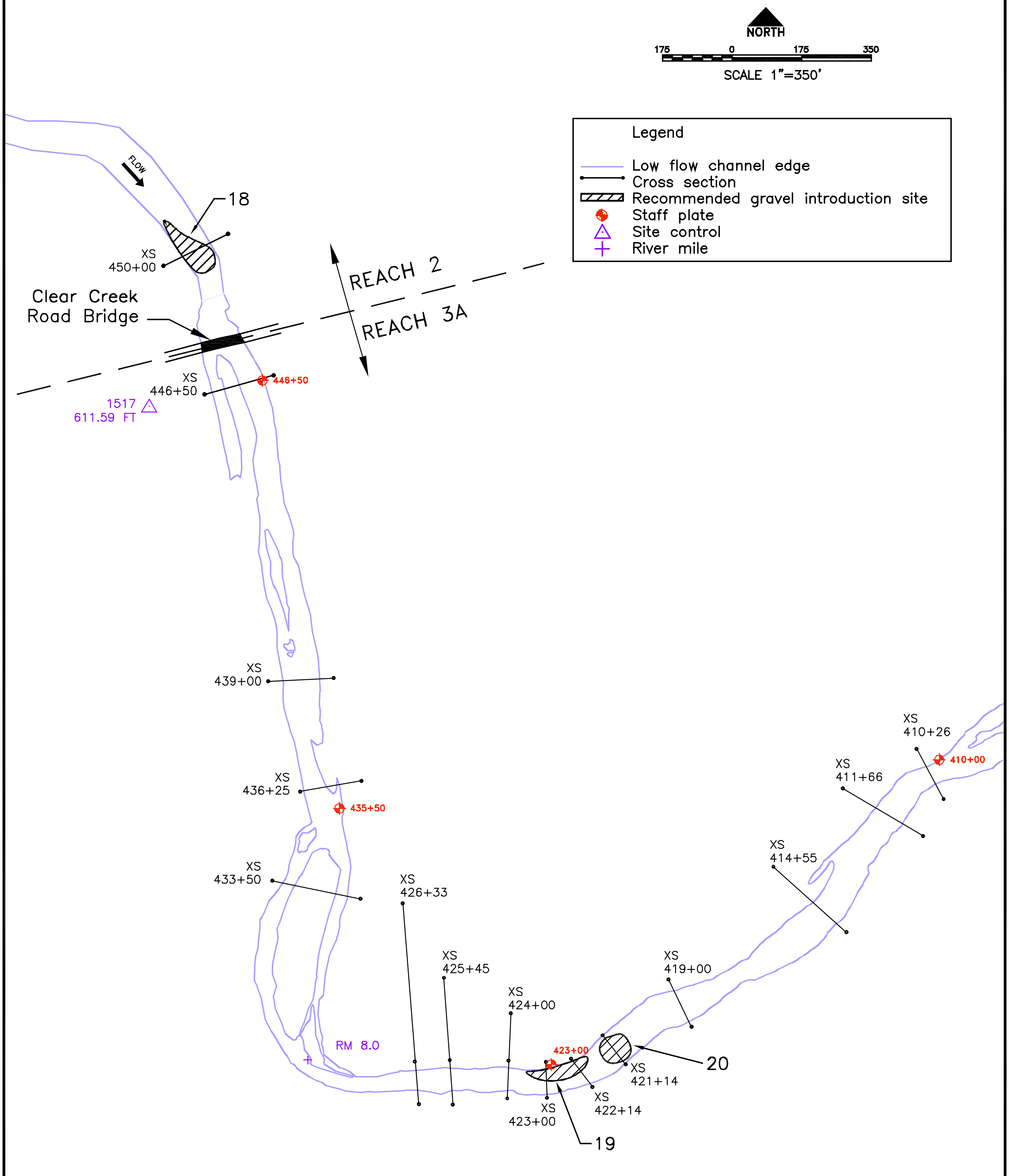

FIGURE 12. LOWER CLEAR CREEK, REACH 2 AND 3A READING BAR RECOMMENDED COARSE SEDIMENT INTRODUCTION LOCATIONS

12/27/01

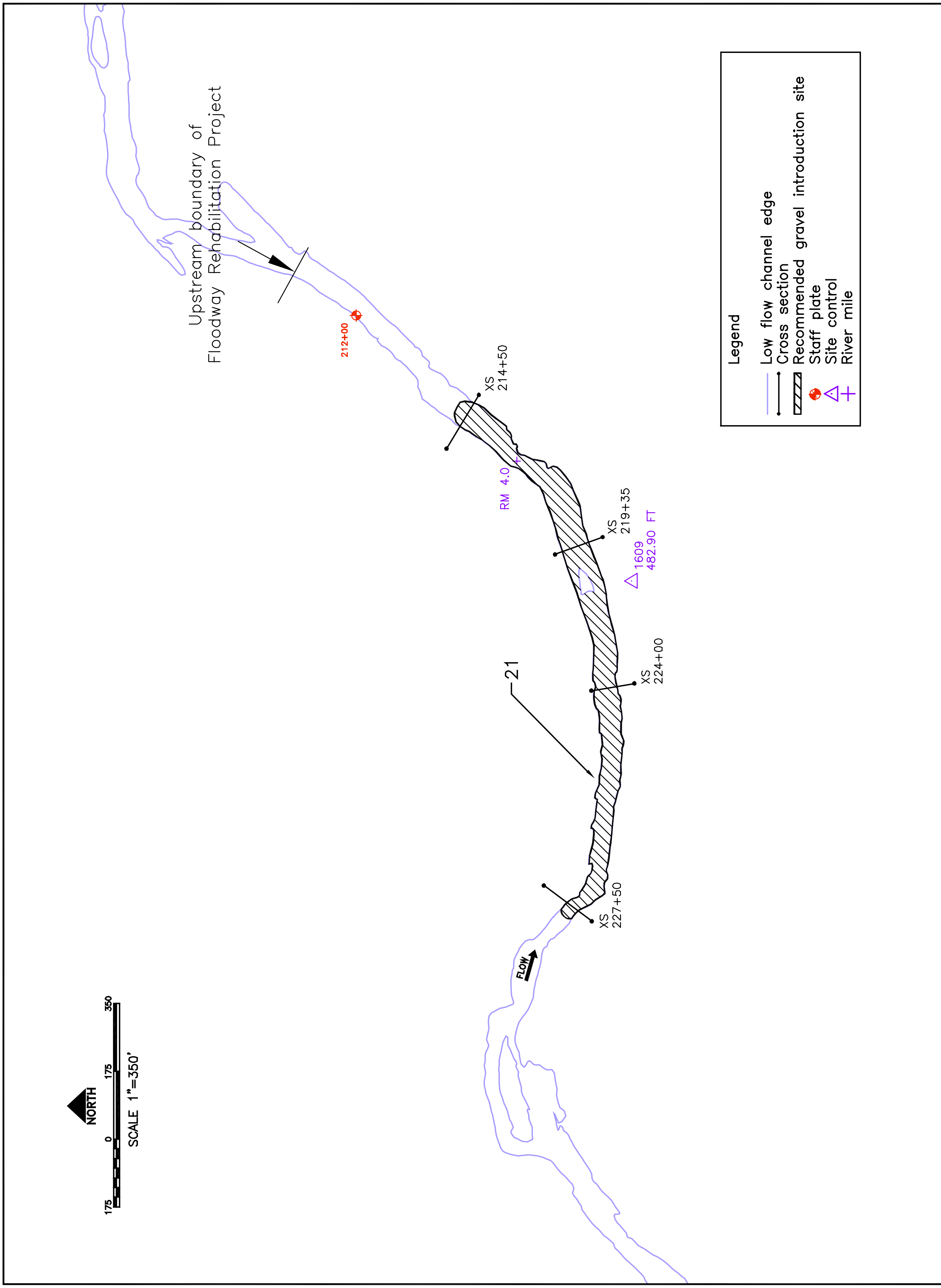

FIGURE 13. LOWER CLEAR CREEK, REACH 4
NORTH STATE AGGREGATES RECOMMENDED COARSE SEDIMENT INTRODUCTION LOCATION

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Figure 14. Recommended gravel introduction morphology at Cross Section 905+20.

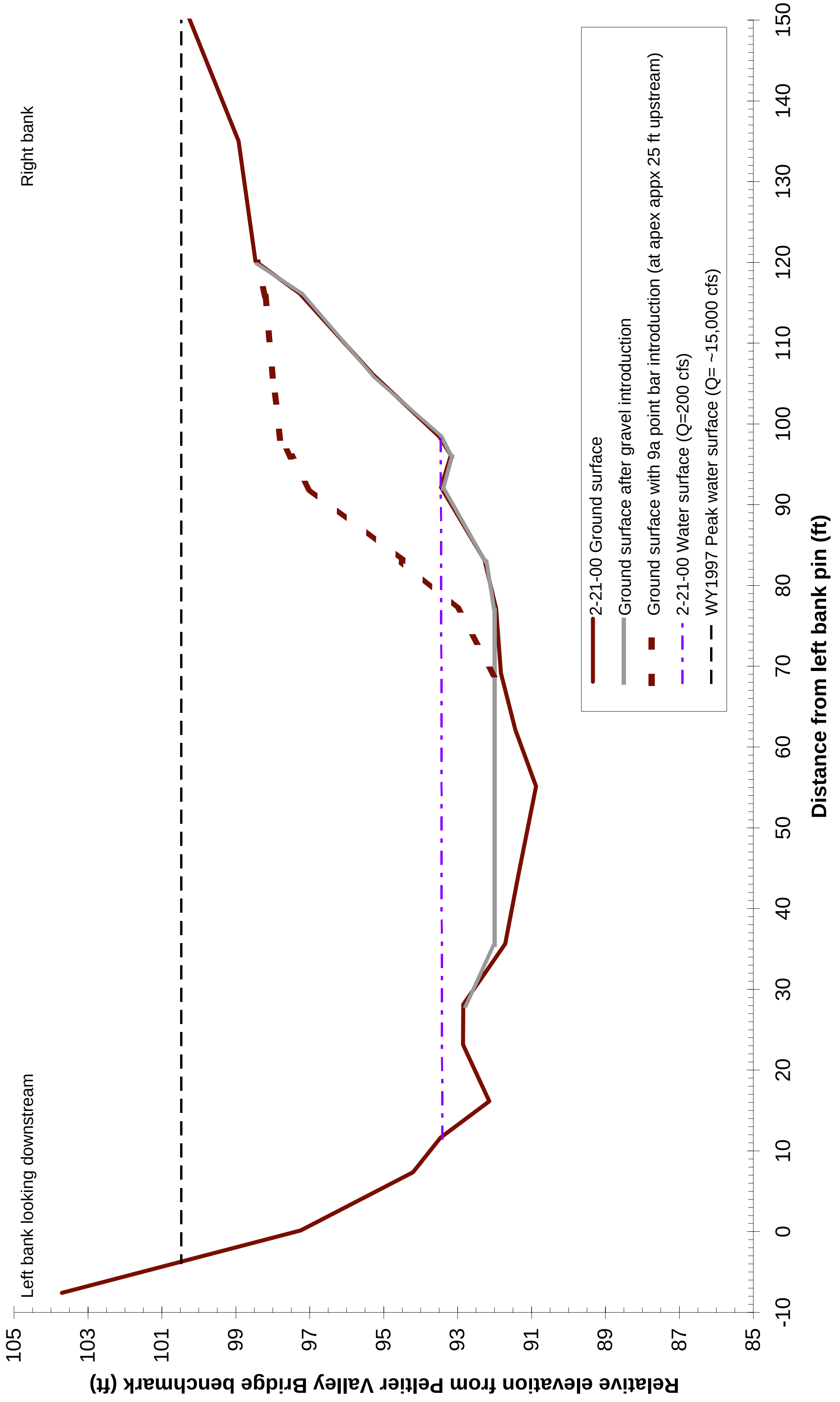


Figure 15. Recommended gravel introduction morphology at Cross Section 900+50

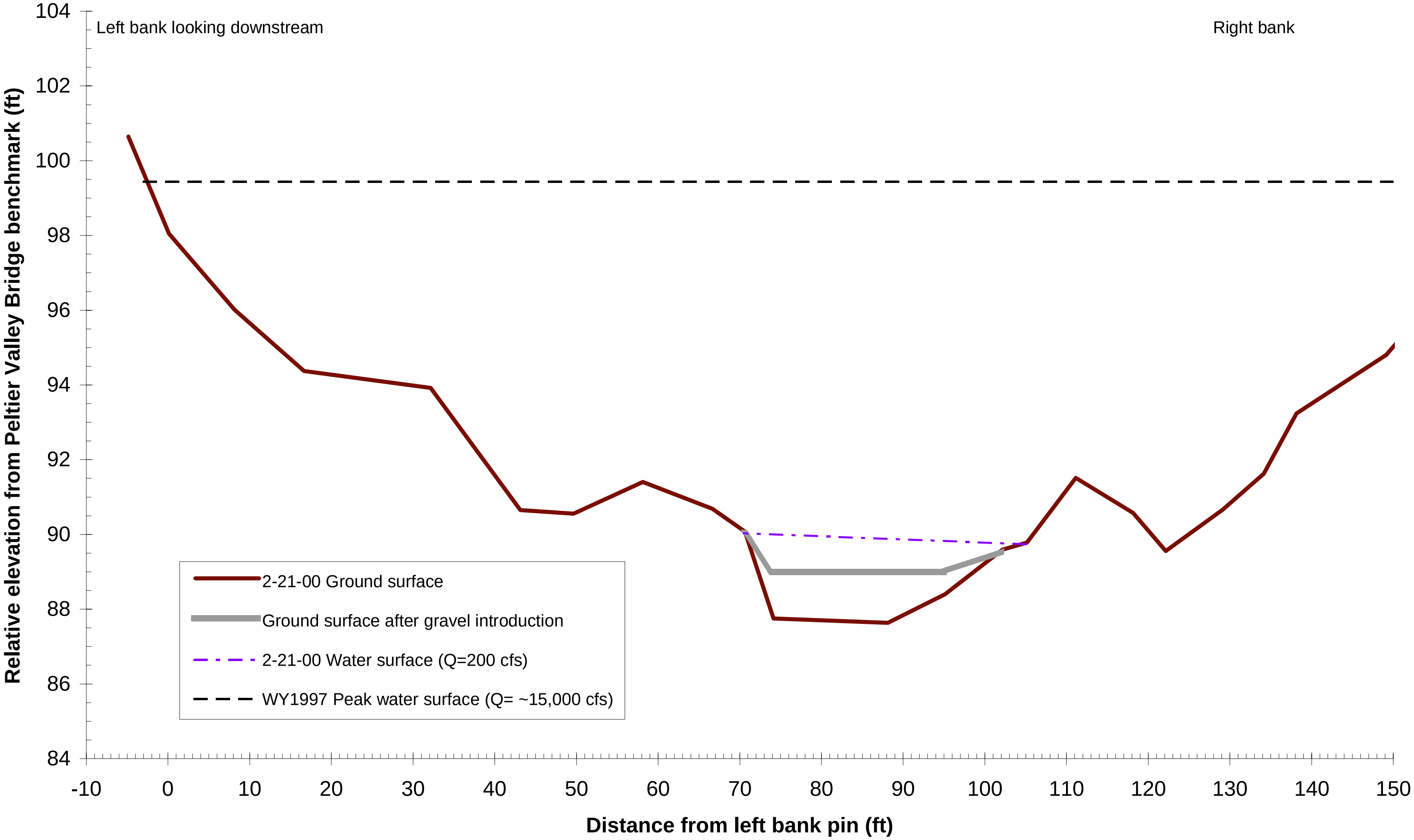


Figure 16. Recommended gravel introduction morphology at Cross Section 896+75.

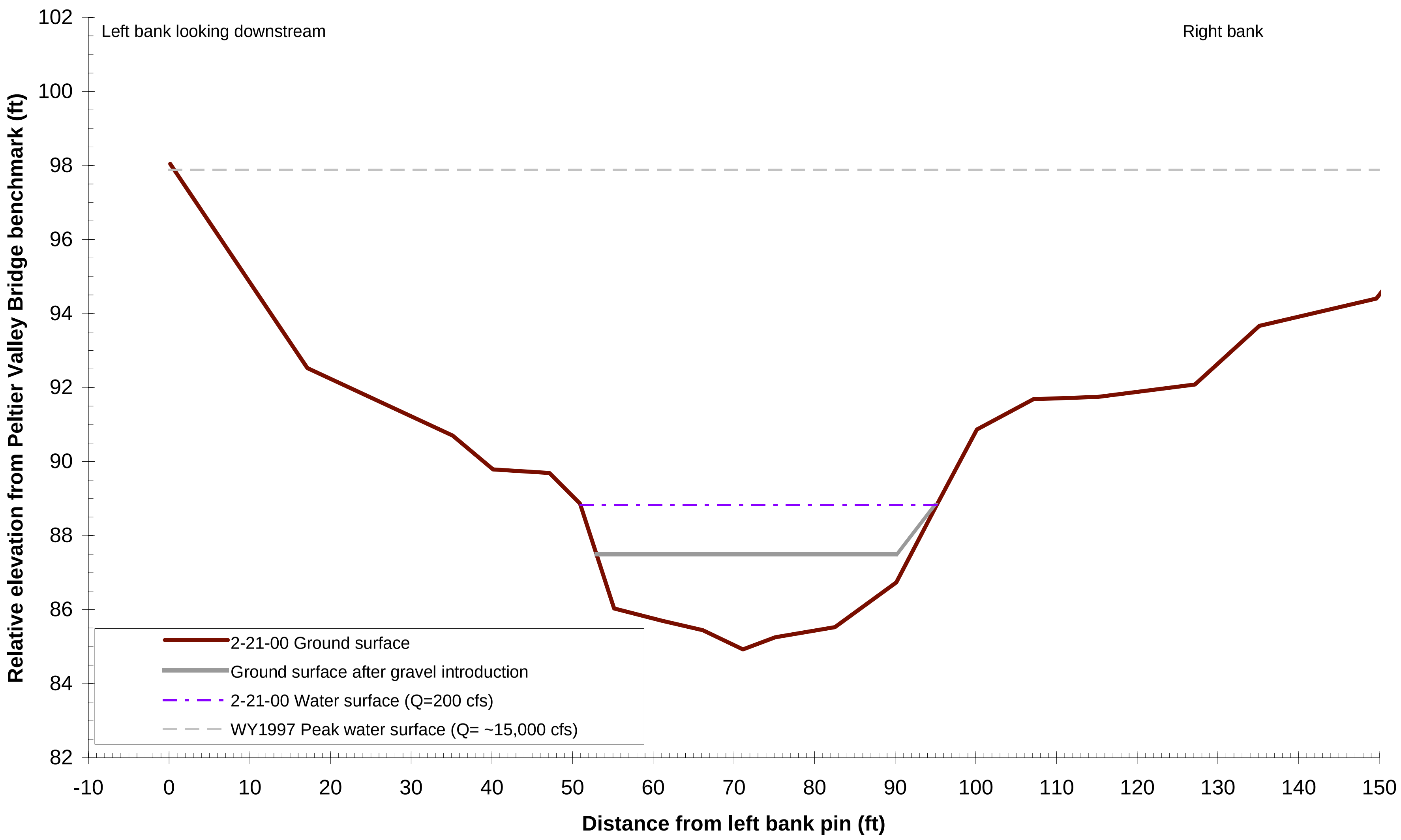


Figure 17. Recommended gravel introduction morphology at Cross Section 894+10.

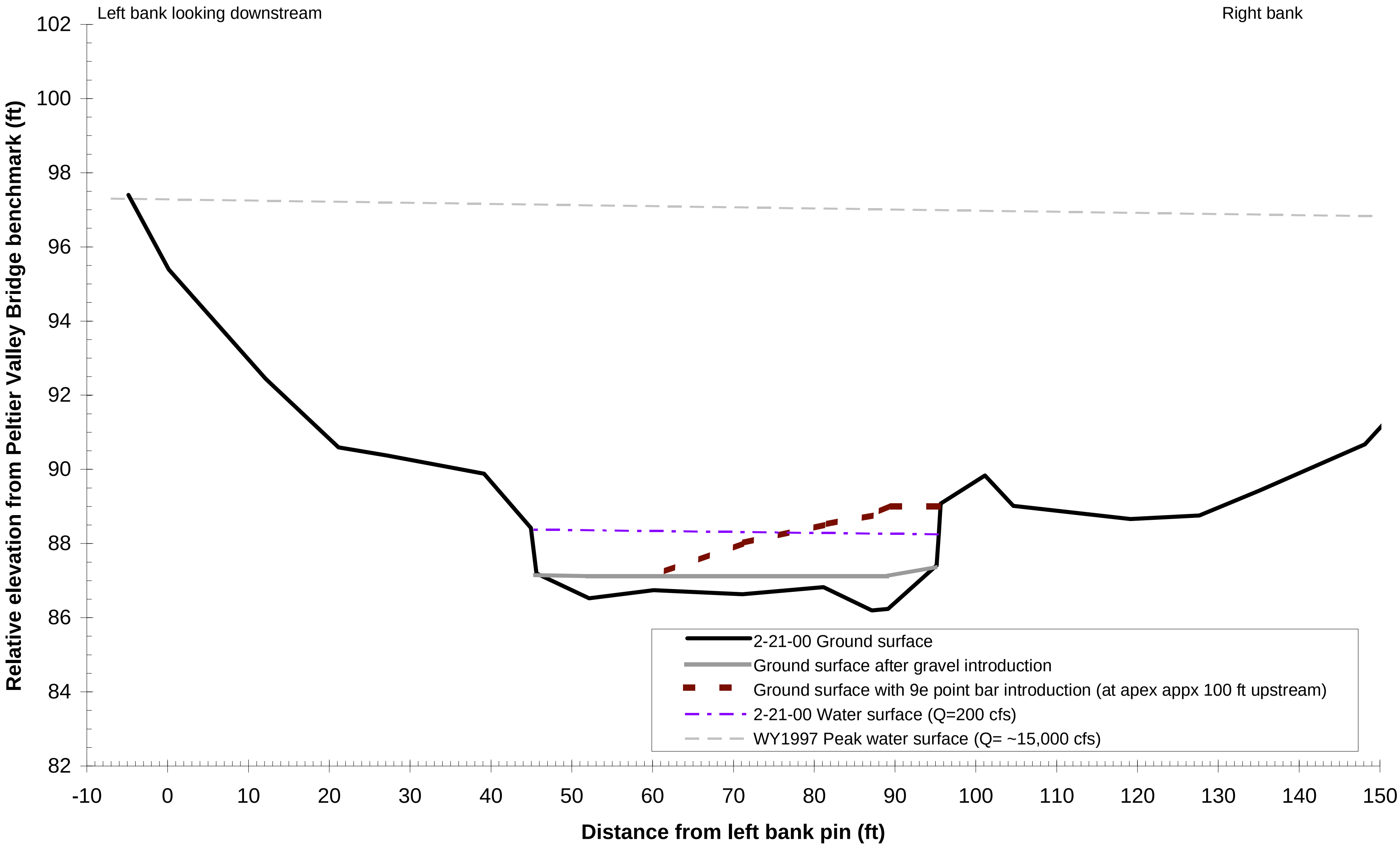


Figure 18. Recommended gravel introduction morphology at Cross Section 891+80.

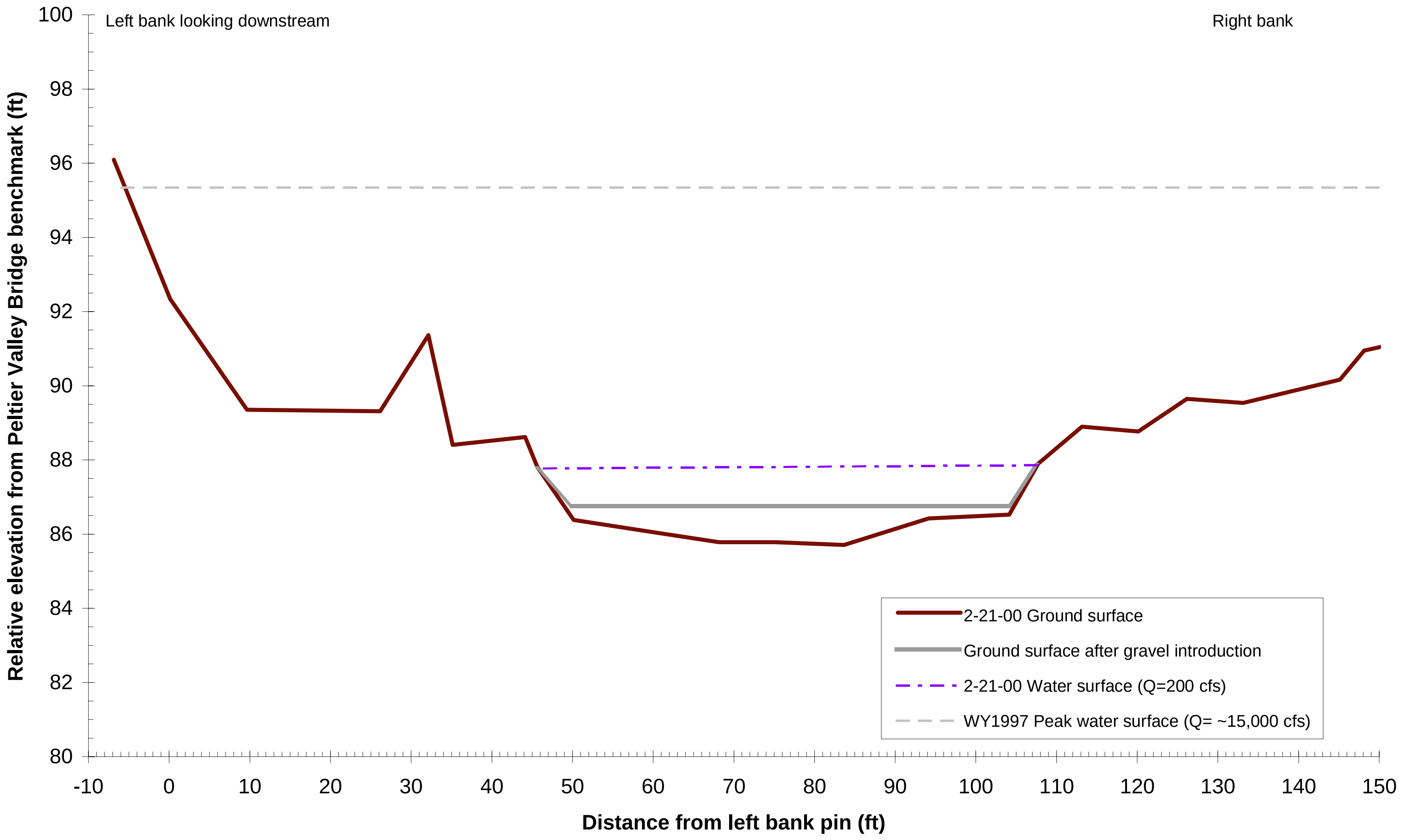


Figure 19. Recommended gravel introduction morphology at Cross Section 888+75 (Introduction NOT recommended to preserve pool depth for adult salmonid holding habitat).

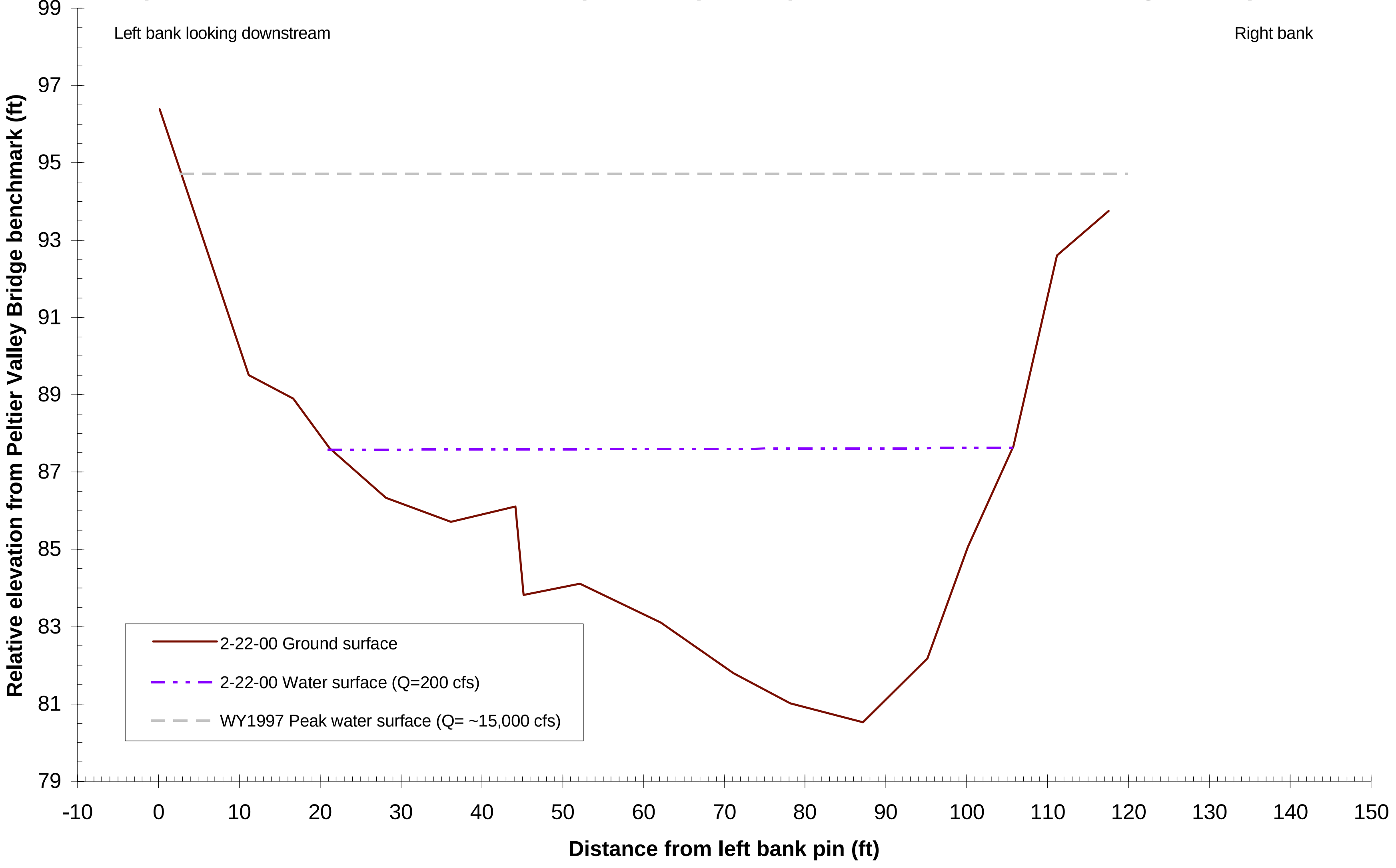


Figure 20. Peltier Valley Bridge longitudinal profile showing recommended gravel introduction morphology

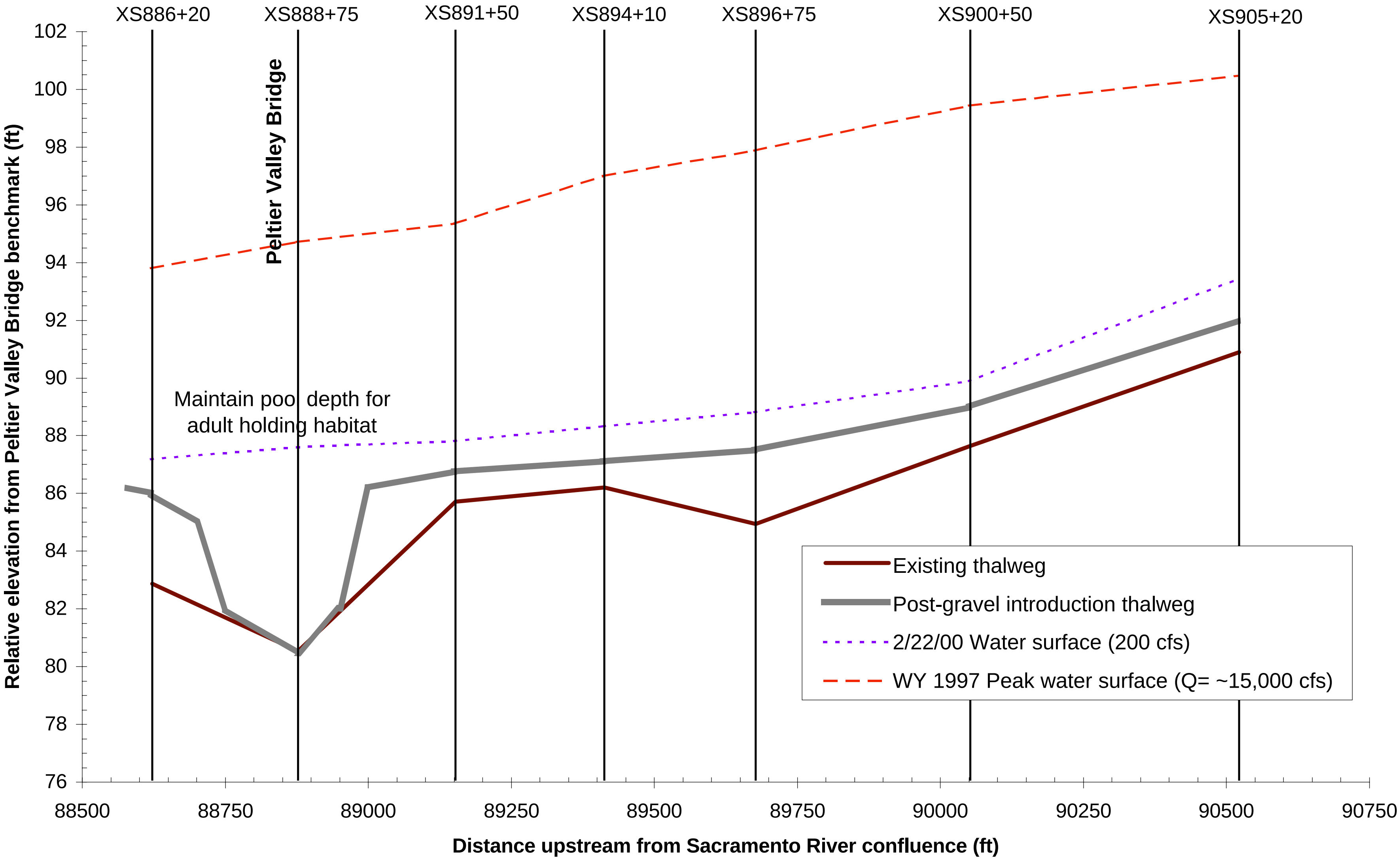


Figure 21. Recommended gravel introduction morphology at Cross Section 886+20.

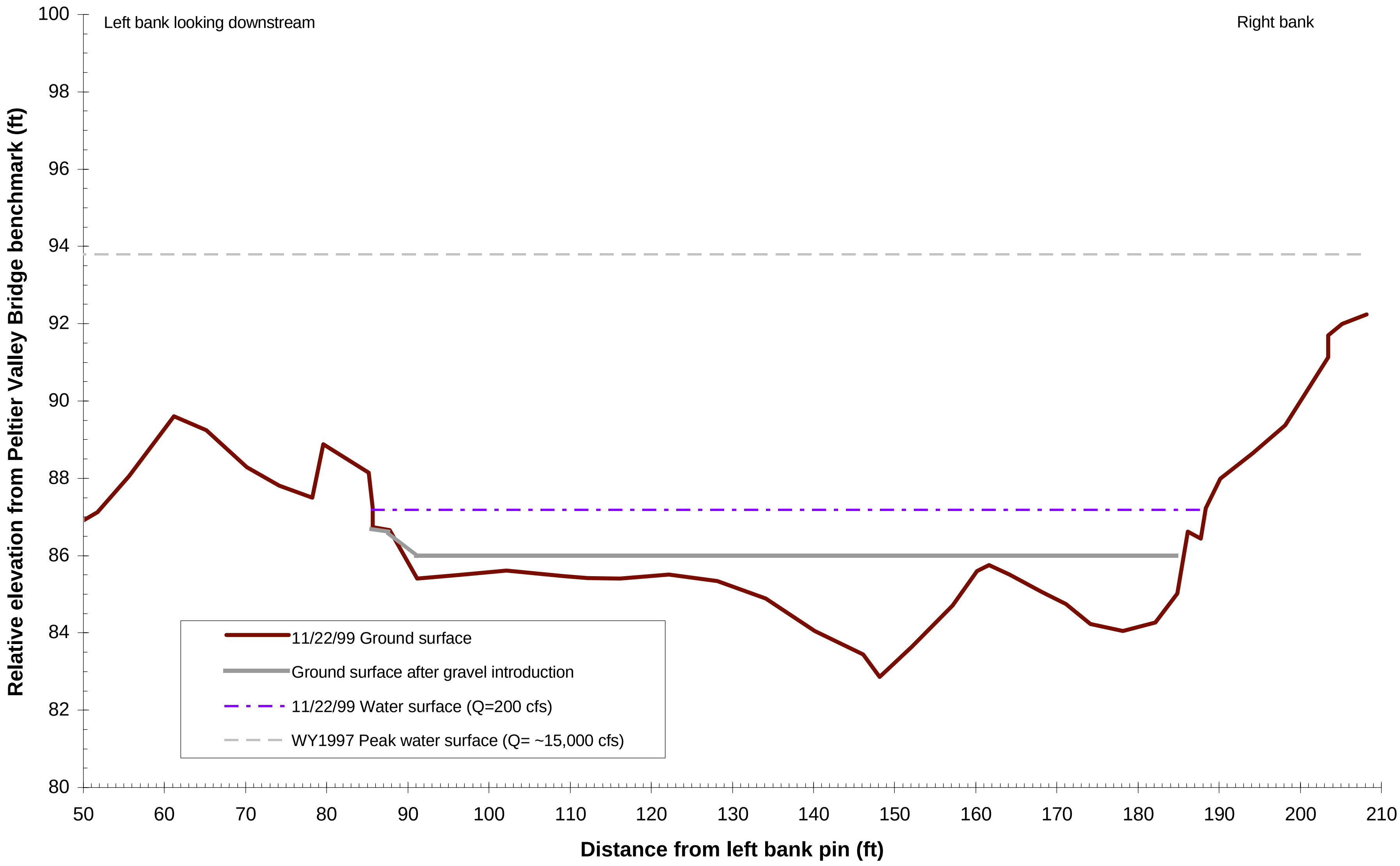


Figure 22. Recommended gravel introduction morphology at Cross Section 878+25.

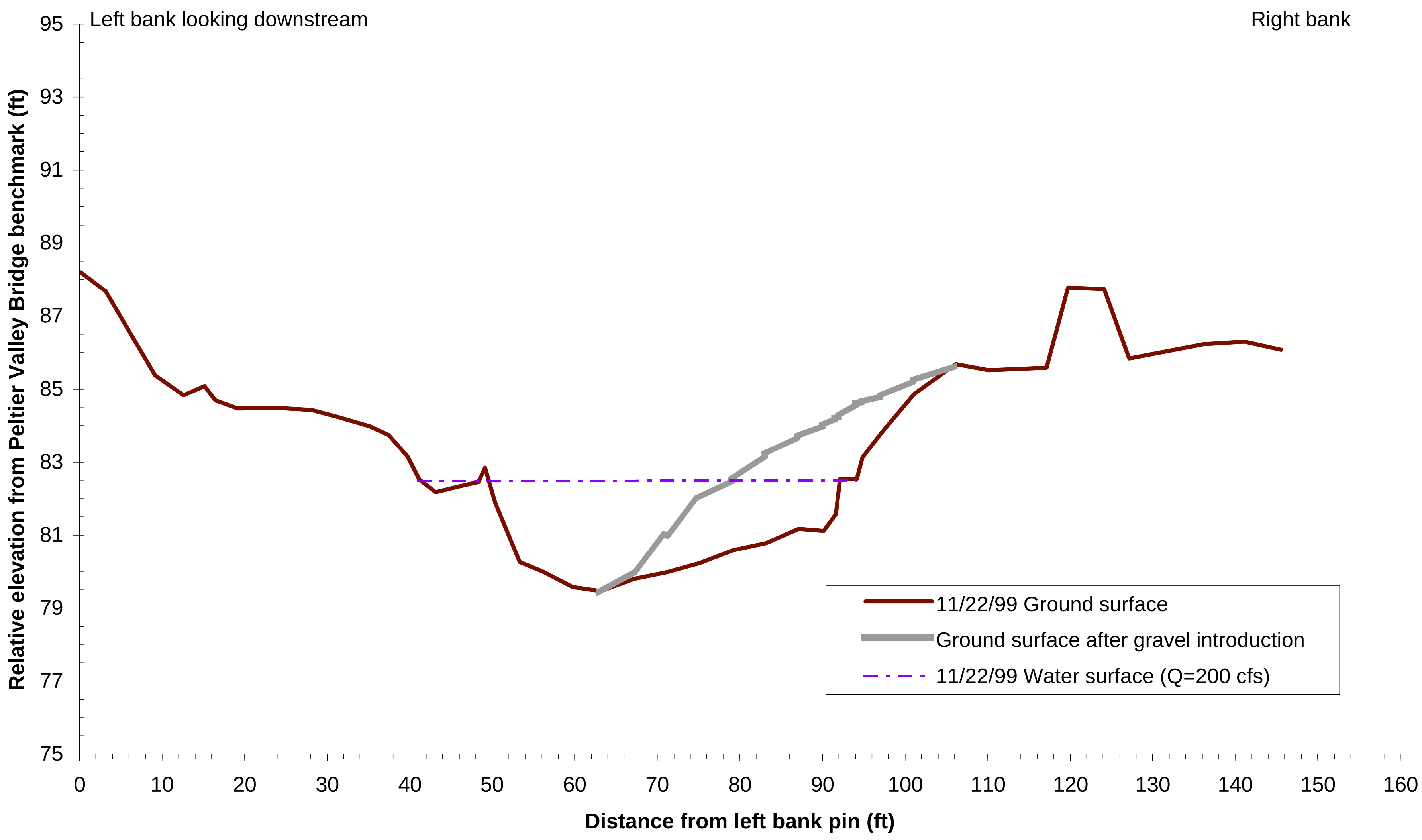


Figure 23. Recommended gravel introduction morphology at Cross Section 875+75.

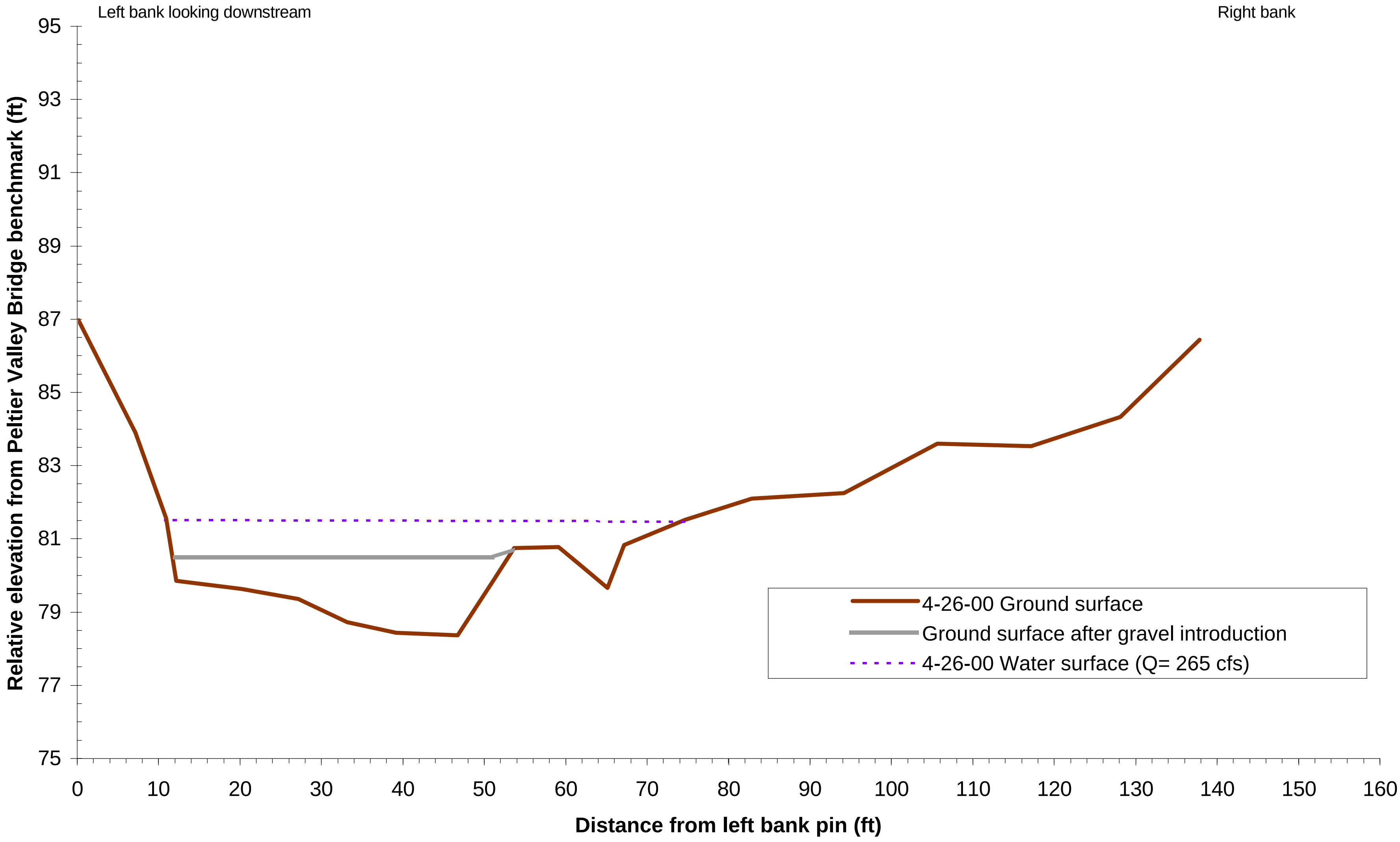


Figure 24. Recommended gravel introduction morphology at Cross Section 870+50.

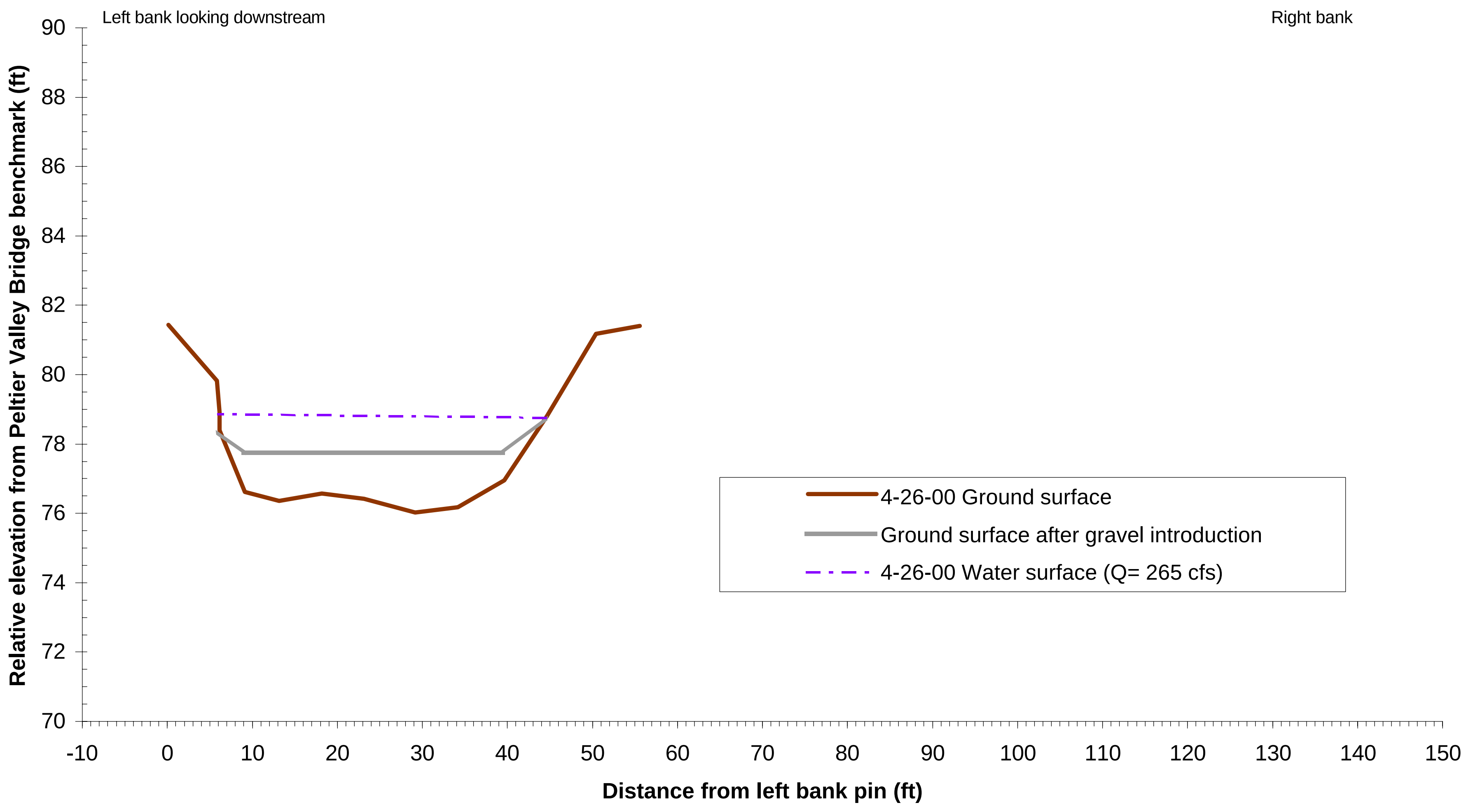


Figure 25. Recommended gravel introduction morphology at Cross Section 861+20.

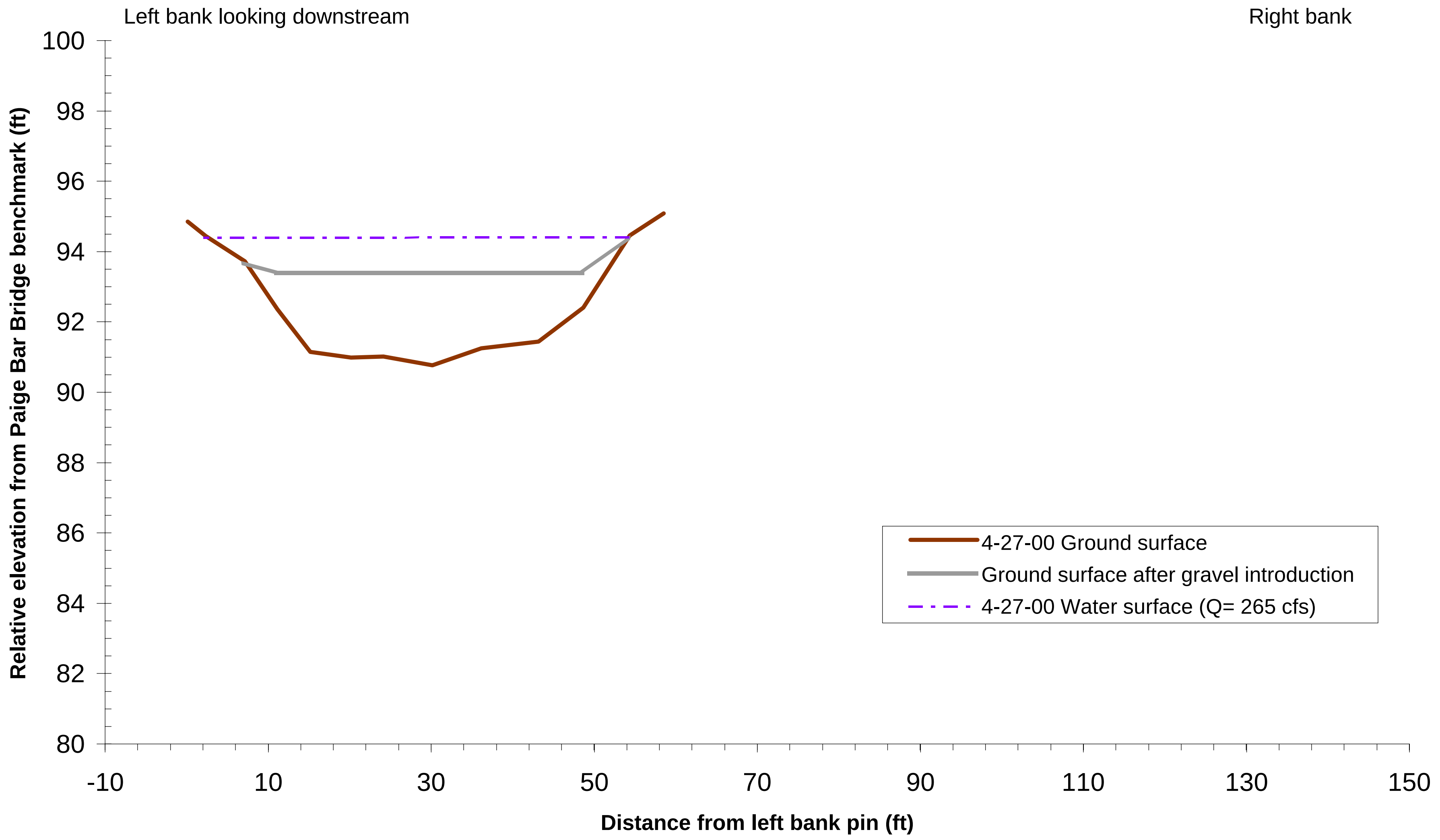


Figure 26. Recommended gravel introduction morphology at Cross Section 860+20.

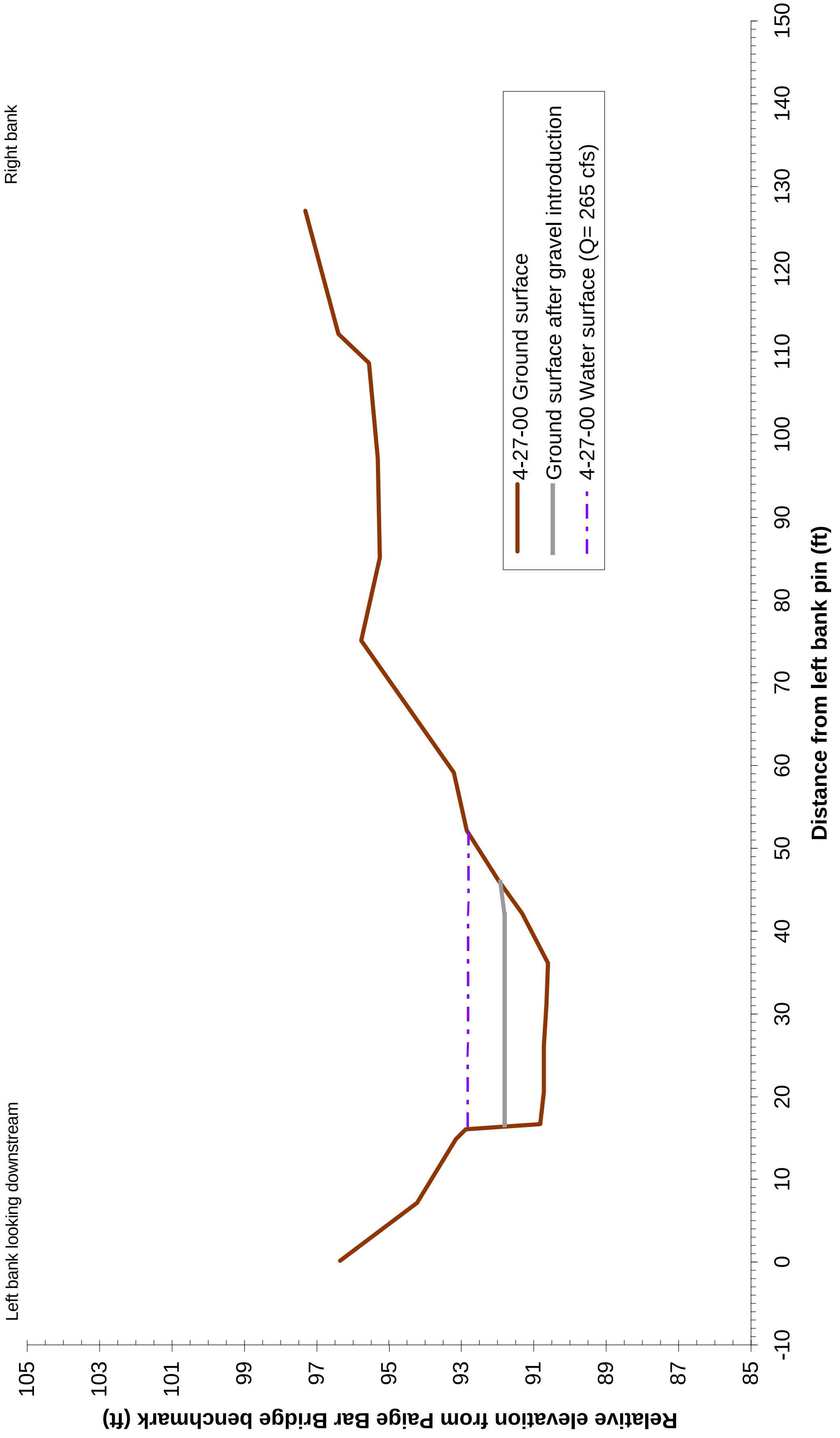


Figure 27. Recommended gravel introduction morphology at Cross Section 857+50

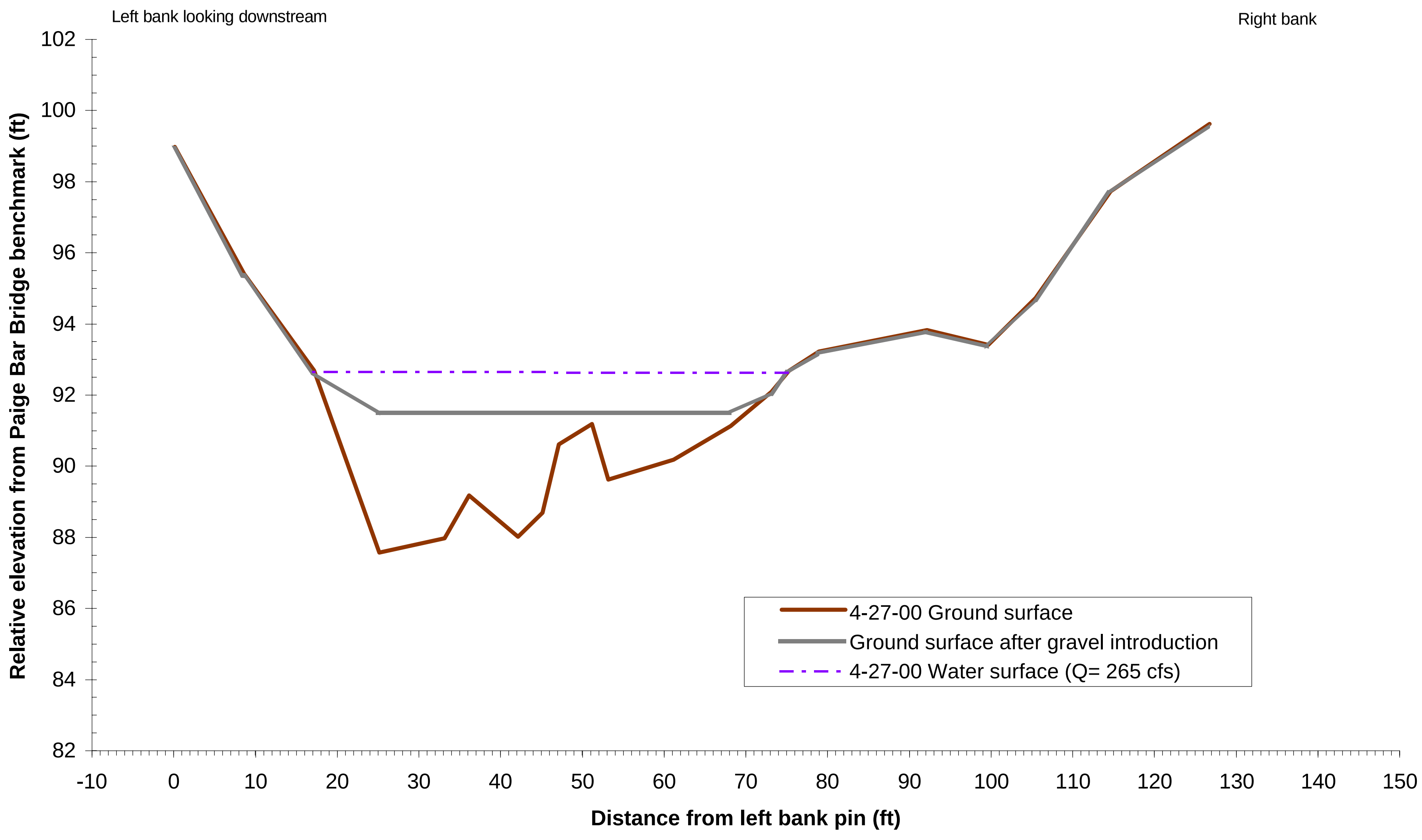


Figure 28. Recommended gravel introduction morphology at Cross Section 848+00.

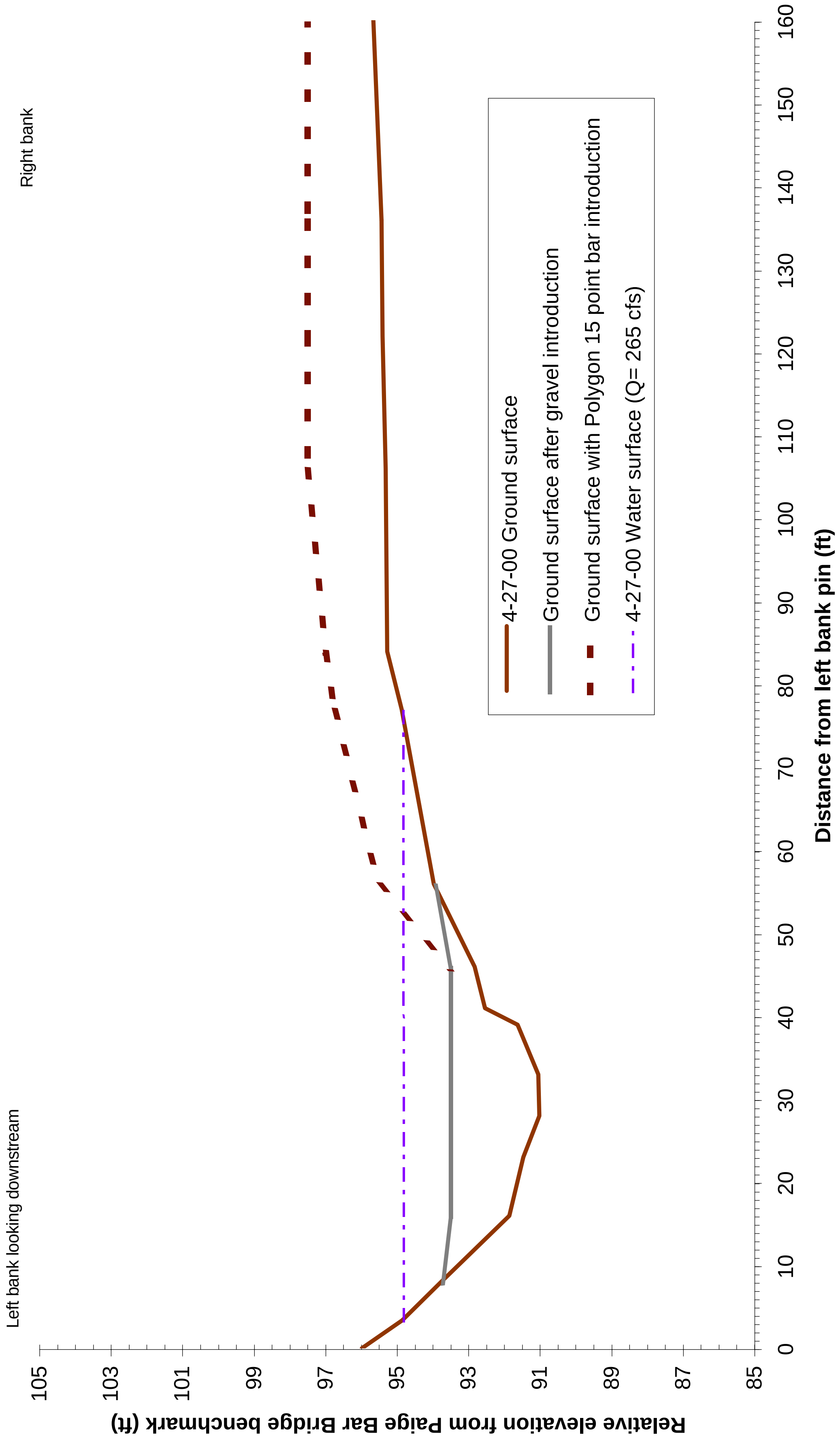


Figure 29. Recommended gravel introduction morphology at Cross Section 570+50.

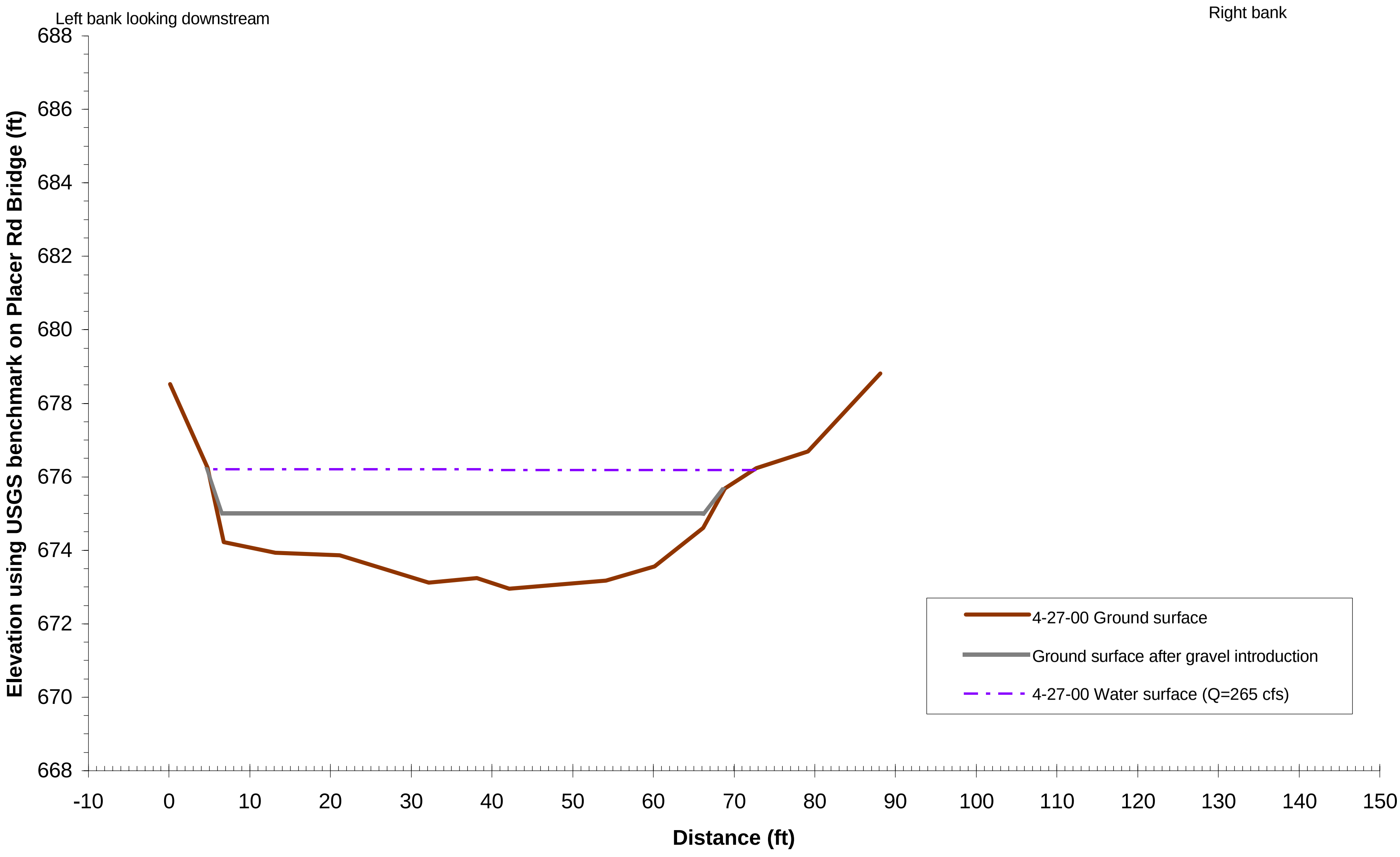


Figure 30. Recommended gravel introduction morphology at Cross Section 568+20.

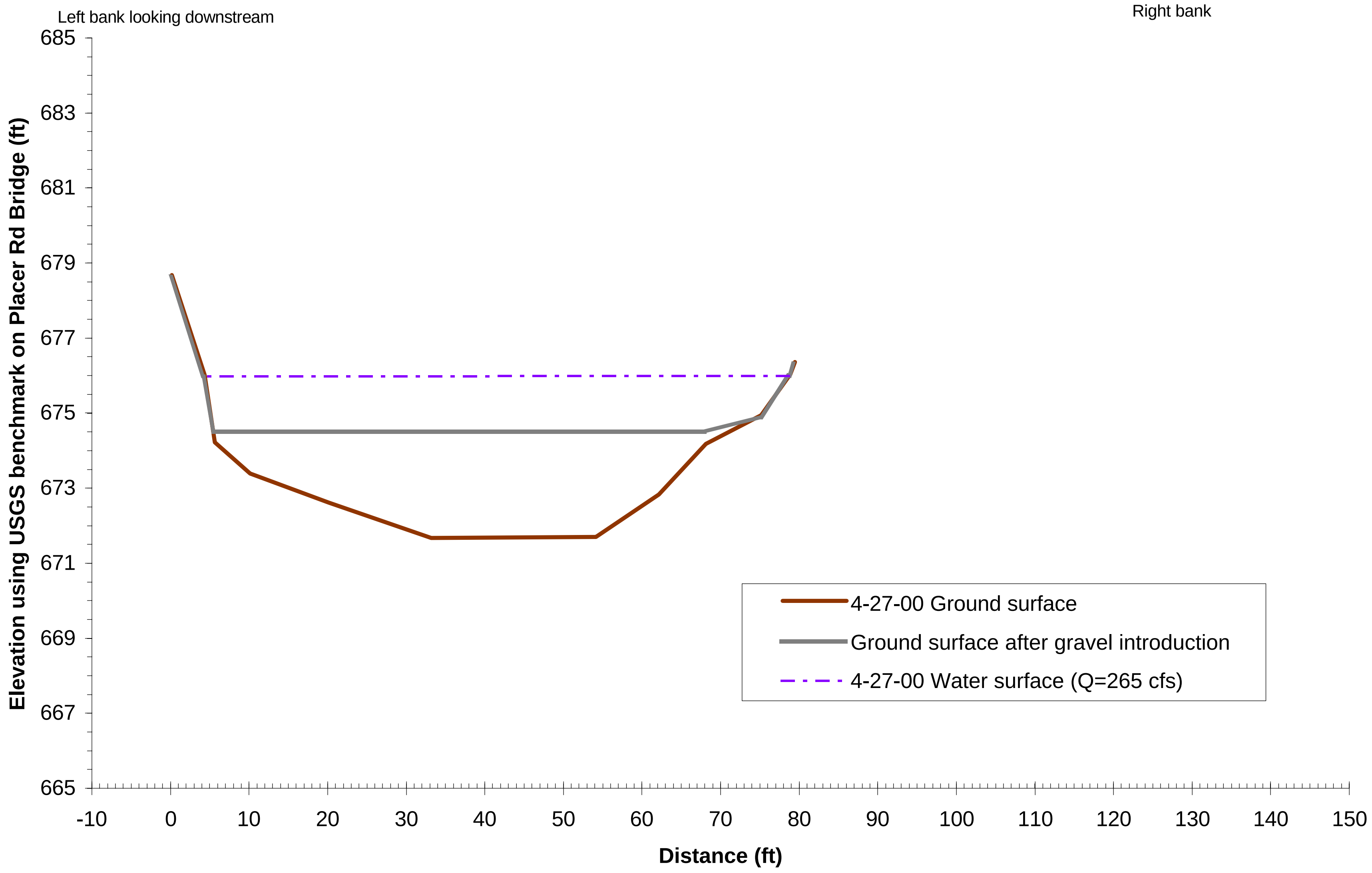
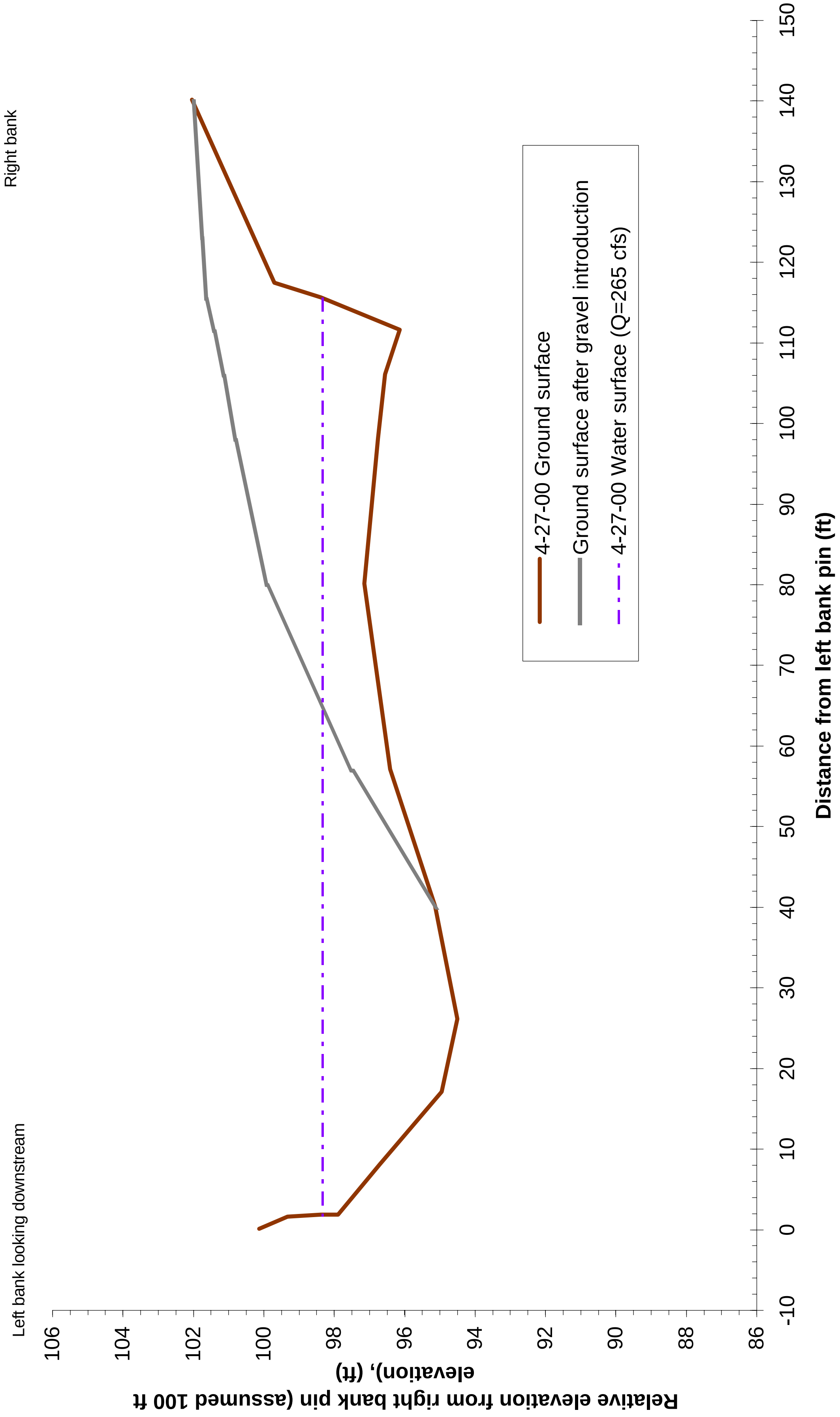


Figure 31. Recommended gravel introduction morphology at Cross Section 450+00



Reach	Figure 10-14 Map Polygon	Location	Reference Cross Section	Surface Area of Added Substrate (ft^2)	Depth of Added Substrate (ft)	Cross Sectional Area of Added Substrate(ft^2)	Representative Length of Channel (ft)	Substrate Volume (yd^3)	Augmentation Method (Figure 5)
	WSRCD SITE	Below Whiskeytown Dam	NO XS					3,000 *	Method 1
1	**1**	Below Whiskeytown Dam	NO XS	9,060	2.5			839	Method 3A
	2		NO XS	3,231	3			359	Method 3B
	3		NO XS	5,275	4			781	Method 3A
	4		NO XS	7,612	2			564	Method 3A
	5		NO XS	6,026	2.5			558	Method 3B
	6		NO XS	2,246	3			250	Method 3A
	7		NO XS	2,749	3			305	Method 3A
	8		NO XS	2,536	1			94	Method 3B
	9	Raise bed from	905+20			26	700	674	Method 2
		XS 905+20 to XS 886+20	900+50			31	410	471	Method 2
			896+75			72	260	693	Method 2
			894+10			25	155	144	Method 2
			891+50			42	253	394	Method 2
			888+75			0	0	0	Method 2
	9a	Point bars from above		1,578	2.5			146	Method 3A
	9b	XS 905+20 to XS 894+10		2,476	2.5			229	Method 3A
	9c			1,743	2.5			161	Method 3A
	9d			5,780	2.5			535	Method 3A
	9e			5,687	2.5			527	Method 3A
	10		886+20			31	150	170	Method 3B
	11	Peltier Bridge Site Corner Pool		6,034	6			1,341	Method 3A
	12	XS 878+25 to below XS 875+75	878+25			61	200	452	Method 3A
			875+75			62	250	574	Method 3B
	13	Above XS 870+50 to XS 860+20	870+50			47	800	1,393	Method 2
			861+20			87	514	1,656	Method 2
			860+20			29	110	118	Method 2
	14	XS 857+50 to XS 848+00	857+50			111	600	2,467	Method 2
			848+00			68	810	2,040	Method 2
	15	Paige Bar	848+00	70,650	3			7,850	Method 3A
		REACH 1 TOTAL GRAVEL VOLUME						**28,785**	
2	**16**	USGS Gaging Station nr Igo	570+50	6,226	2			461	Method 3B
	17		568+20	10,853	2			804	Method 3B
	18	Clear Creek Bridge (upstream)	450+00			224	300	2,489	Method 3A
		REACH 2 TOTAL GRAVEL VOLUME						**3,754**	
3A	**19**	Lower Reading Bar	423+00			111	128	526	Method 3A
			422+14			92	95	324	Method 3A
	20		421+14	4,436	2			329	Method 3B
		REACH 3A TOTAL GRAVEL VOLUME						**1,179**	
3B	**WSRCD SITE**	Saeltzer Canyon USBR/WSRCD gravel augmentation site						3,000 *	Method 1
		REACH 3B TOTAL GRAVEL VOLUME						**3,000 ***	
4	**21**	RM 3.8 - 4.3 Upstream of Floodv	227+50			6	130	29	Method 2
			224+00			106	674	2,646	Method 2
			219+35			78	413	1,193	Method 2
			214+50			86	257	819	Method 2
		REACH 4 TOTAL GRAVEL VOLUME						**4,687**	
		TOTAL POTENTIAL GRAVEL "TRANSFUSION" VOLUME						**41,404**	

*** first year, thereafter introduce gravel volumne at rate equal to gravel export as shown on repeat cross section surveys**

Table 2. Coarse sediment introduction volume estimates in lower Clear Creek, CA.

Reach 3A. Reading Bar was recently regraded to create functional floodplains as part of the Floodway Rehabilitation Project. Historically, dredge tailings confined the creek, resulting in higher than normal sediment transport capacities in this reach and very little coarse sediment storage. Removal of the confining dredge tailings, restoration of floodplains, and restored access for anadromous salmonids by removing Saeltzer Dam makes it an important reach to improve coarse sediment storage. In addition to the site discussed above at the downstream end of Reach 2, we recommend that gravel introduction supplement a large point bar at Cross Sections 423+00 and 422+14, as well as a pool tail at cross section 421+14 (Figure 12, Figures 32-34). Introducing gravels at this site will help supply coarse sediment downstream to the former Saeltzer Dam site. Approximately 1,200 yd^3 of gravel could be placed at this site (Table 2).

Reach 3B. The reach below the former Saeltzer Dam site should continue to be supplied with gravel to restore the channel thalweg and bed elevation. Now that the dam has been removed, gravel routing from upstream sources should greatly improve, eliminating the need for additional introduction here in the future. In addition, sediment introduction at this site will improve in-channel supply in the uppermost portion of Reach 4 where a majority of the fall run chinook salmon spawning occurs. Gravel routing from this reach is essential to maintain supplies for transport into the Floodway Rehabilitation Project just downstream. We recommend that the WSRCD continue adding gravel in the 3,000 yd^3 range as has been done over the past five years.

Reach 4. The Floodway Rehabilitation Project will provide a large-scale gravel transfusion to restore the instream and off-channel storage of coarse sediment and improve bedload routing in the reach. The project will import a combined total of approximately 500,000 yd^3 of coarse sediment to restore degraded conditions left by aggregate extraction. Sediment from this reach will eventually route to the Sacramento River, restoring bedload transport continuity throughout the entire lower alluvial reach from the former Saeltzer dam site to the Sacramento River. Channel rehabilitation, however, will not include the short channel reach from RM 3.8 to RM 4.3, which would therefore remain in sediment deficit and interfere with sediment transport continuity to the restored reaches downstream. Cross sections surveyed in this reach indicate the channel has degraded by at least 3-4 ft, with exposed hardpan evident throughout much of the reach. A secondary channel was cut through the left bank during recent high flows (1997 and 1998), which has steepened the thalweg gradient. Several cross sections and a longitudinal profile were surveyed in this reach to determine an approximate gravel transfusion volume. We recommend approximately 4,700 yd^3 of sediment be placed to raise the thalweg elevation off the clay hardpan, restore an alternate bar morphology, and provide gravel supply to the Floodway Rehabilitation Project (Figure 13, Figures 35-39, Table 2).

4.3 Long-term maintenance of coarse sediment storage

Because of the severity of the coarse sediment deficit in several reaches of Clear Creek access limitations, the initial transfusion process cannot immediately restore coarse sediment storage to the ideal equilibrium conditions in all reaches of the corridor. Thus sediment sink areas will require considerable time to fill to allow full sediment routing through the corridor. These bedload sinks capture the coarse sediment transported from upstream reaches, but inhibit transport continuity to downstream reaches until storage in the entire reach is filled. The canyon reaches on Clear Creek (Reaches 1 and 2) may require several years of high flows and gravel introduction before all storage sites are filled and coarse sediment transport continuity is restored.

We recommend locating long-term sediment introduction sites just downstream of bedload impedance reaches, and therefore at the upstream ends of restored sediment transfusion reaches, thereby maintaining supply within these reaches. Periodic sediment introduction volumes should approximately equal the volume of sediment transported downstream during high flows. These long-term sites assume that the

Figure 32. Recommended gravel introduction morphology at 423+00.

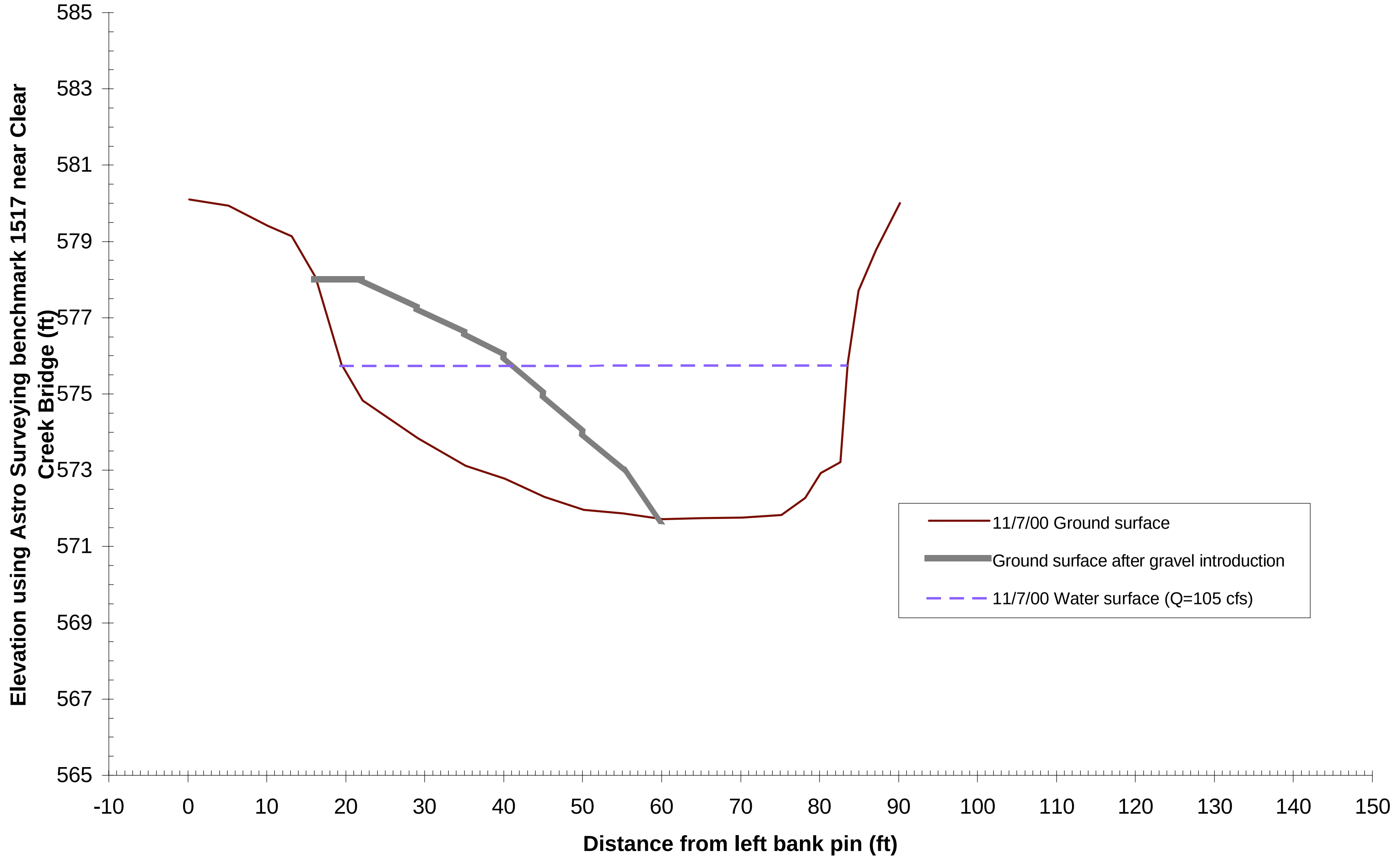


Figure 33. Recommended gravel introduction morphology at 422+14.

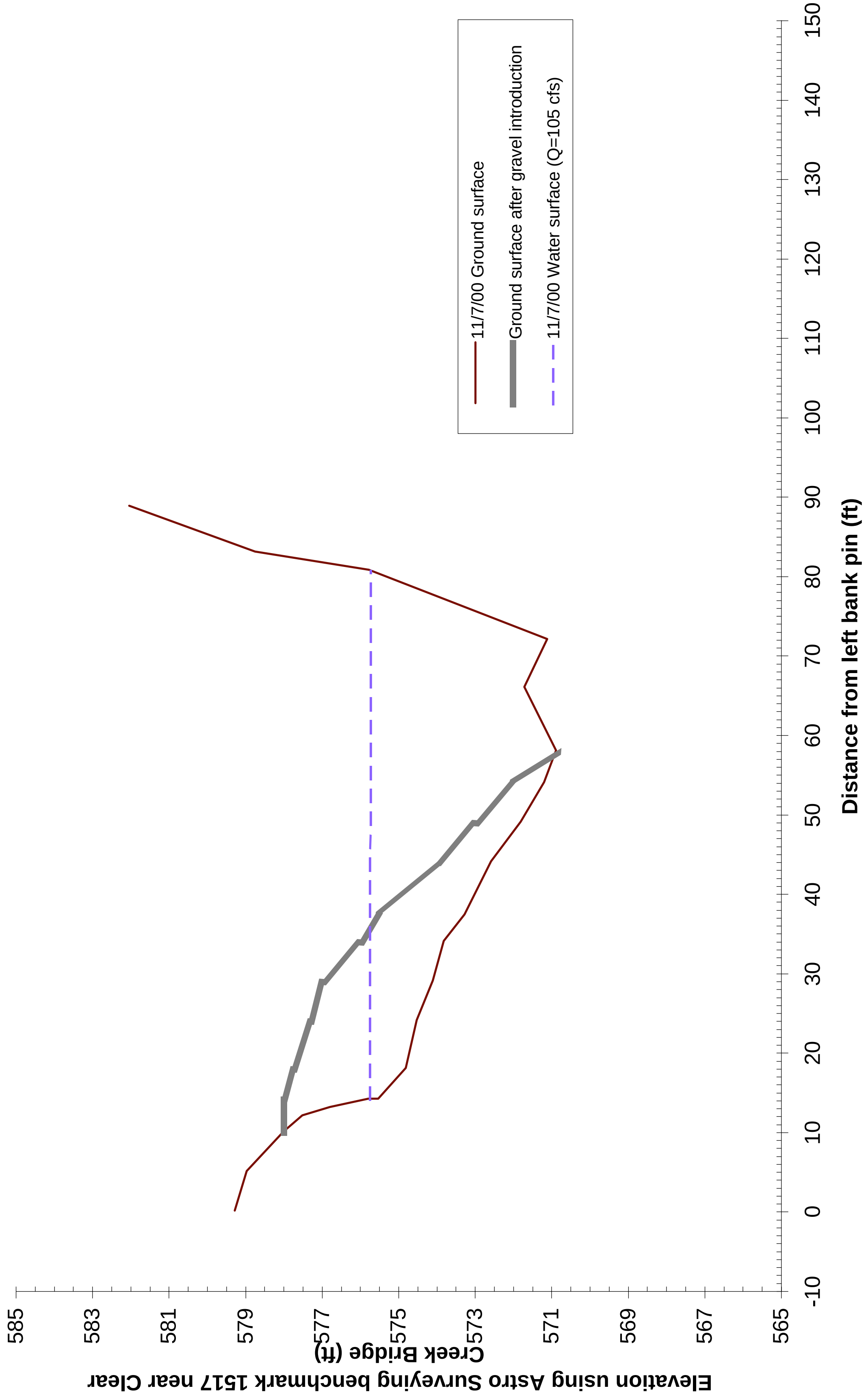


Figure 34. Recommended gravel introduction morphology at 421+14.

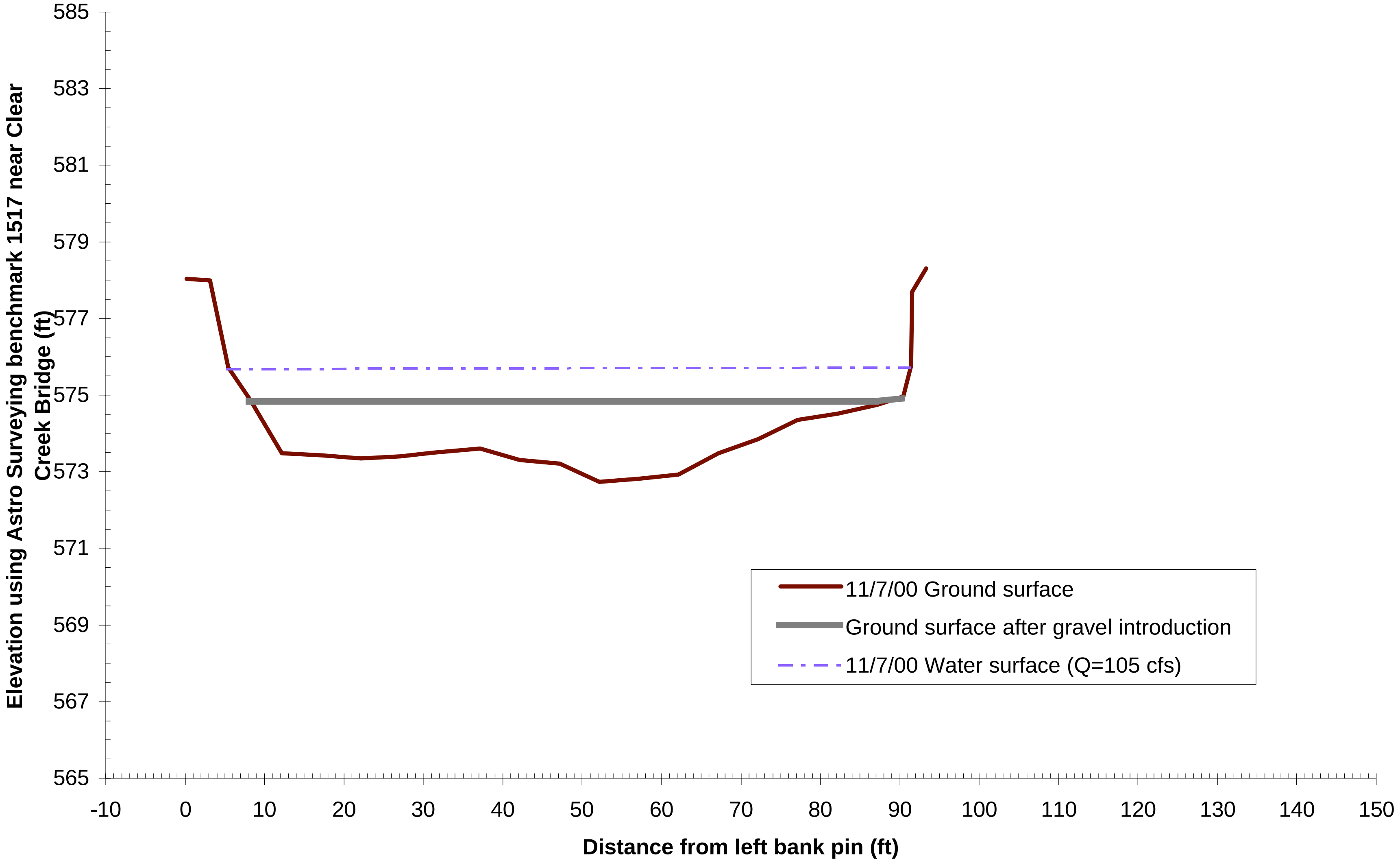


Figure 35. Recommended gravel introduction morphology at 227+50.

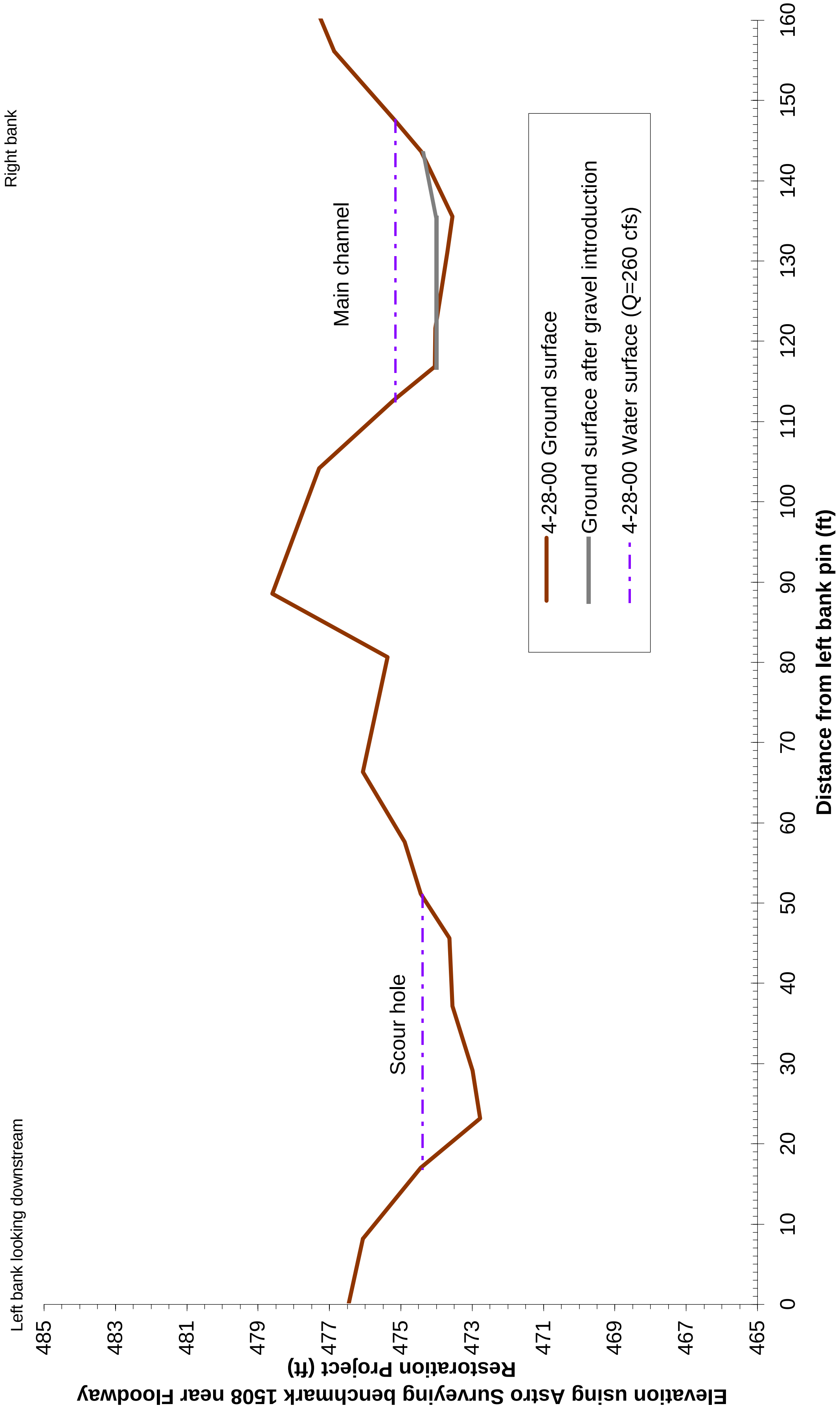


Figure 36. Recommended gravel introduction morphology at 224+00.

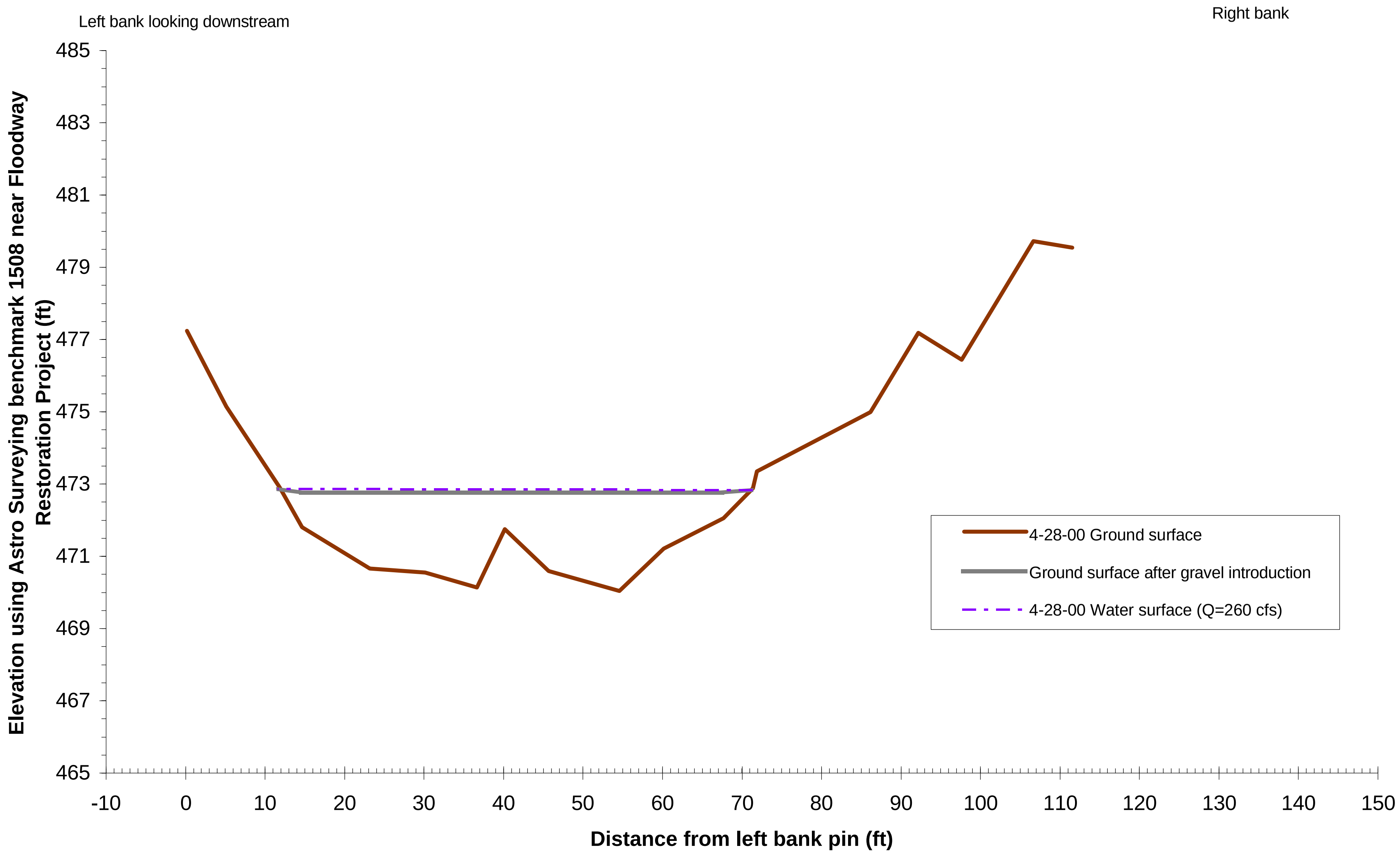


Figure 37. Recommended gravel introduction morphology at 219+35.

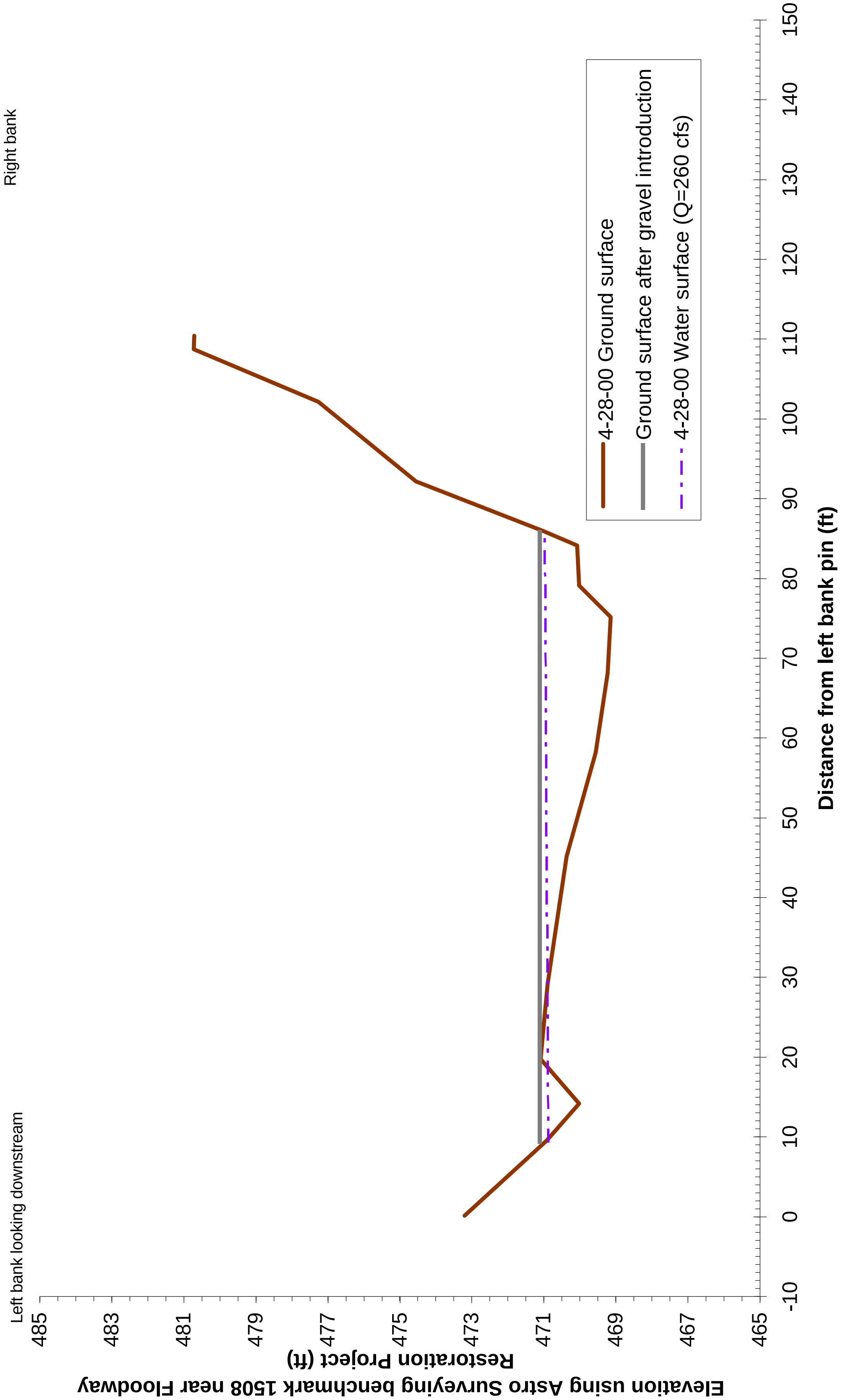


Figure 38. Recommended gravel introduction morphology at 214+50.

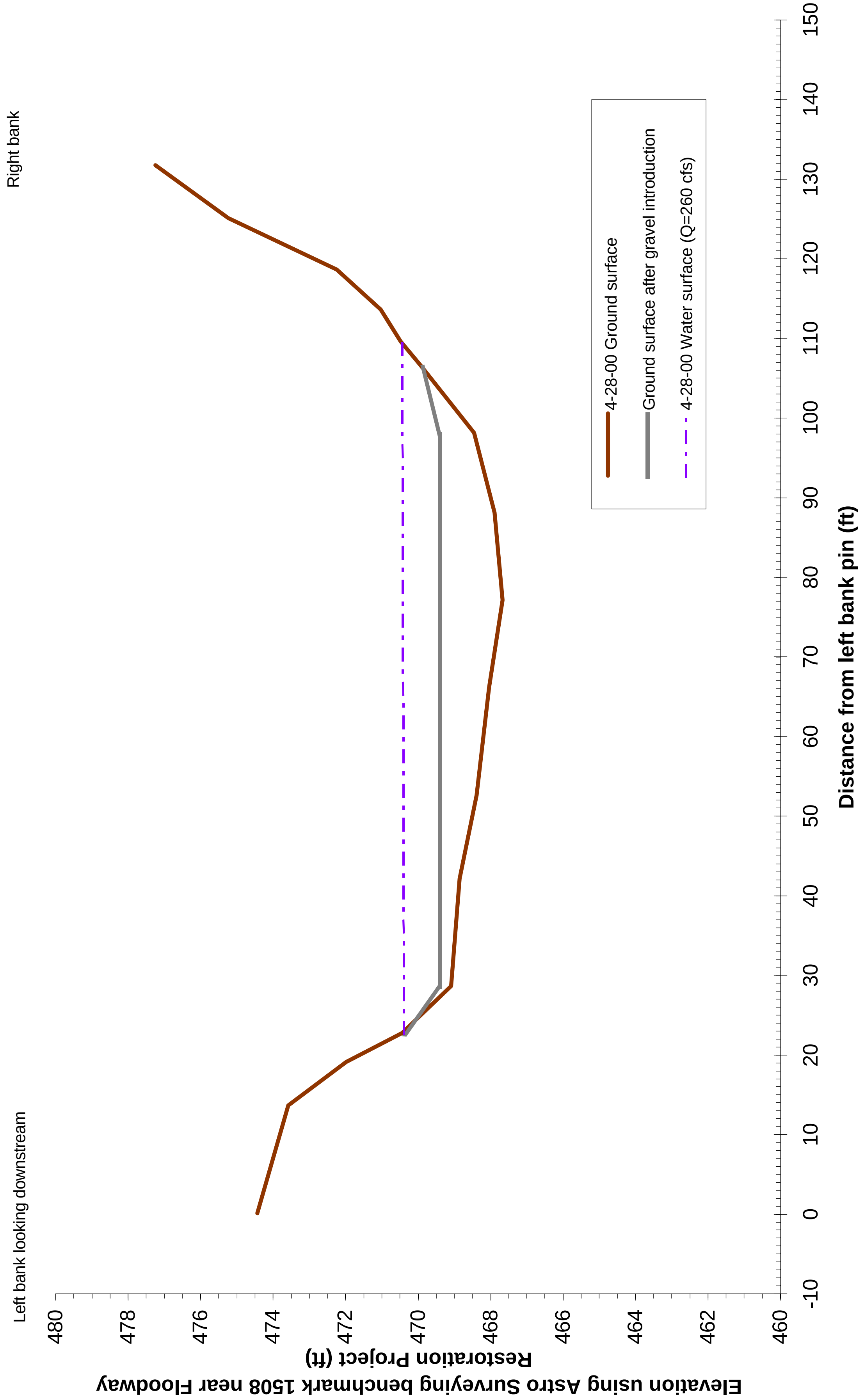
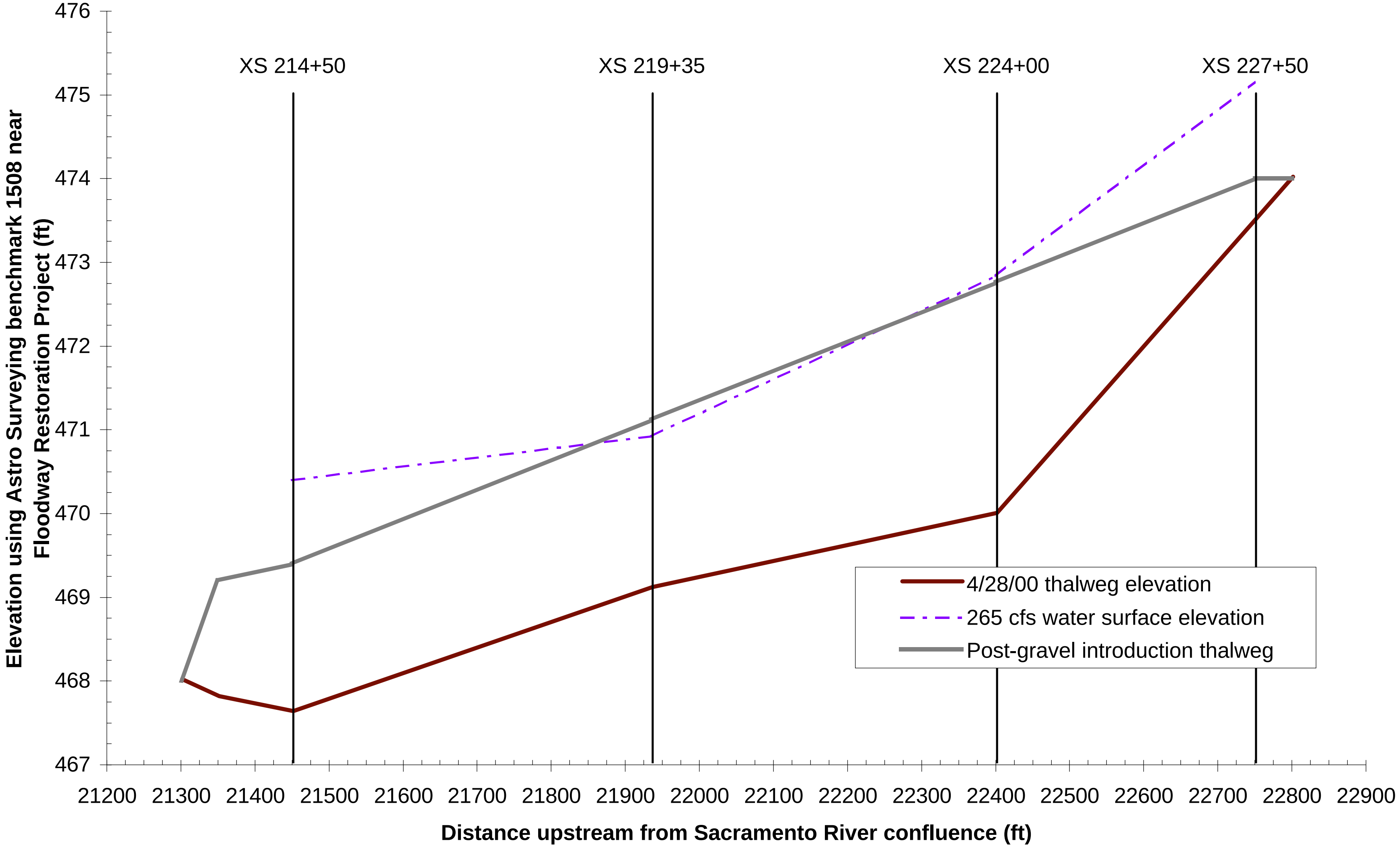


Figure 39. North State Aggregates longitudinal profile showing recommended gravel introduction morphology



recommended short-term gravel transfusion phase is implemented completely. These annual introduction sites are:

- Site 1, below Whiskeytown dam, intended to maintain sediment supply from the dam down to Paige Bar Bridge (Figure 10A). This is a **high priority** site intended to contribute to spring chinook salmon and winter run steelhead habitat rehabilitation.
- Site 2, at the Igo Gaging Station below the Placer Road Bridge (Figure 11). This site is intended to maintain habitat in this reach as sediment is transported downstream. This site is **medium priority** based on the short-term longevity of introduced gravels that would quickly be transported through the downstream Canyon Reach during high flows.
- Site 3, downstream of the Clear Creek Bridge (Figure 12). This site is intended to maintain coarse sediment supply and salmonid habitat in the alluvial reaches downstream of Clear Creek Bridge. These sediments will eventually route through the former Saeltzer Dam site, into the lower alluvial reaches to provide long-term maintenance of the Floodway Rehabilitation Project. This site is also **high priority** due to its strategic location at the upstream end of the alluvial reaches of Clear Creek. This site will require long-term maintenance until the Canyon Reaches are no longer bedload impedance reaches and gravel is routing from sites 1 and 2.
- Site 4, at the USBR/WSRCD introduction site below the former Saeltzer Dam site. This site is a **low priority** site due to the recent removal of Saeltzer Dam and the unpredictable consequences of sediment routing downstream from the former dam site. Additionally, there has already been approximately 27,000 tons (appx. 18,000 yd^3) added there since 1996.
- Site 5, above the Floodway Rehabilitation Project at North State Aggregates (Figure 13). This site is a **high priority** site due to its role in maintaining coarse sediment supply to the floodway rehabilitation project. The priority of this site should eventually decrease as gravel from upstream sites begin to route through this reach and supply the Floodway Rehabilitation Project.

Ideally, once coarse sediment storage has been restored and begins to fully route through lower Clear Creek, the above sites should gradually be deleted, with the exception of Site 1. Site 1 will always be required because Whiskeytown Dam blocks all coarse sediment supply from the upper watershed.

Annual volumes of sediment introduction required to maintain long-term equilibrium should eventually be determined by a combination of information from bedload transport measurements and from repeat cross section surveys. These tools are dependent on collection of data before, during, and after high flow events that are rare on Clear Creek. Several bedload transport measurements have been collected at moderate flows (1,000 cfs to 3,200 cfs). Bedload transport monitoring at the Renshaw Riffle and cross section monitoring at all introduction sites should continue indefinitely as part of the gravel management program.

4.4 Gravel Composition

Gravel size preferences vary with fish species and by life stage. For spawning adult chinook salmon, considerable research has been conducted to describe suitable spawning gravel size compositions. For example, Raleigh (et al. 1986) reported the optimal mix for chinook salmon ranging from 20 to 106 mm. Chambers (1956) reported suitable gravel mixes of: 21% for 3 to 12.5 mm; 41% for 12.5 to 60 mm; 24% for 60 to 100 mm; and 14% for 60 to 150 mm. Allen and Hassler (1986) developed profiles of habitat requirements for chinook salmon in the Pacific Southwest, and site Bell's (1973) findings that optimal gravels range from 13 to 102 mm, and that 80% of the particles should range from 13 to 51 mm, and the remaining 20% from 51 to 103 mm. This size range also agrees with Thompson (1972) as cited in Bjornn and Reiser for fall chinook salmon. Platts et al. (1979) reported spawning gravel mixes from the South Fork Salmon River, Idaho containing 84% of 10 to 76 mm, and the remaining greater than 76 mm. Finally, Kondolf and Wolman (1993) compiled published and original reports containing spawning gravel size distribution data for salmonids, and noted a large range of spawning gravel sizes used by chinook salmon. Describing the ideal or definitive spawning gravel mixture is thus not possible.

We recommend a gravel mixture that includes a very small percentage of particles in the smaller gravel size range (from 1/8” to 1”) (Table 3). Gravel mixtures with a similar size range composition have been utilized on the Stanislaus River, where the gravel introduction program is targeting both chinook salmon and steelhead (Mesick 2000). Post-project monitoring on the Stanislaus River has indicated that chinook salmon also show a preference for gravel compositions that include a percentage of smaller grain sizes.

Table 3. Recommended gravel composition for introduction in lower Clear Creek, developed to provide suitable spawning gravels for chinook salmon and steelhead.

Percent of Total	**Particle Size (mm)**	**Particle Size (inches)**
5%	3 to 12.5 mm	1/8 ” to 1/2”
10%	12.5 to 19.1 mm	1/2” to3/4”
30%	19.1 to 25.4 mm	3/4” to 1”
35%	25.4 to 51 mm	1” to 2”
20%	51 to 127 mm	2” to 5”

This gravel mixture equates to approximately 80% finer than 51 mm (2 inches), with D_{50} = 28 mm and D_{84} = 60 mm. We recommend using a spawning gravel mixture that conforms as closely as is practical to the above mixture, but that does not exceed the 20% recommended for the larger 2” to 5” component.

5 MONITORING

Because of the unique approach proposed for sediment management, these recommendations should be implemented within the context of a monitoring and adaptive management program designed to (1) evaluate the experimental placement and morphological evolution of introduced gravels, (2) estimate the annual volumes of sediment needed to maintain an equilibrium supply, and (3) quantify changes in quantity, quality, and use of restored habitat by salmonids. These three objectives are essential to an adaptive management and monitoring program. Additionally, monitoring associated with sediment management should test hypotheses (not trends) designed to explain causative processes. For example, introduction of specified substrate size distributions (D_{50}=20, 40, or 60 mm) should be linked to reduced sediment transport thresholds, more frequent bedload mobilization, and increased relative use of different gravel sizes by spawning salmonids. Walters and Holling (1990) note that defining testable hypotheses is trivial, but generating hypotheses sensitive to changes in the function or processes of the ecosystem is more complex. The ultimate monitoring objective should be to quantify the benefit of the management action (sediment introduction) to the project goal (restore habitat and smolt production).

Specific monitoring protocols should include the following:

- Develop a sediment transport rating curve (relationship) relating flow to the annual sediment transport rate; this relationship should be developed for the downstream alluvial reaches; upstream reaches should rely on repeat cross section surveys due to the difficulty in sampling these high energy reaches;
- Continue to calibrate a sediment transport curve to be used in conjunction with empirical data to predict/estimate annual sediment transport volumes; models should encompass similar reaches as empirical relationships are developed (i.e., gravel bed reaches);
- Document distance introduced gravels are transported downstream to document when full sediment routing is achieved;

- Document changes to thresholds in channelbed mobility, related to flood frequency and introduced gravel composition;
- Document changes in channel morphology caused by sediment introduction and transport, with cross section and thalweg profile surveys at established study sites, and topographic surveys with total station in locations suited for it;
- Document occurrence and formation of alluvial features, such as point bars, pools, riffles, etc. by planform mapping;
- Document changes in spawning gravel quantity and quality by planform mapping of spawning habitat, and spawning gravel particle size and permeability analysis.

6 REFERENCES

Allen, M.A., and T.J. Hassler. 1986. *Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Southwest) –chinook salmon*. U.S. Fish and Wildlife Service Biological Report 82(11.49). US Army Corp of Engineers, Tuolumne River EL-82-4. 26 pp.

Bell, M.C. 1973. *Fisheries handbook of fisheries requirements and biological criteria*. U.S. Army Corp of Engineers, Fish Eng. Res. Program. Portland Oregon.

Burner, C.J. 1951. *Characteristics of spawning nests of Columbia River salmon*. US Fish and Wildlife Service Fishery Bulletin 52: 97-110.

Coots, M. 1971. Unpublished California Department of Fish and Game data, Millard Coots, Redding, CA.

Chambers, J.S. 1956. *Research relating to study of spawning grounds in natural areas*. U.S. Army Corp of Engineers, North Pacific Division, Fish Eng. Res. Program. p 88-94.

Kondolf, G.M., and M.G. Wolman. 1993. The sizes of salmonid spawning gravels. *Water Resources Research*, 29(7): 2275-2285.

Lutrick, E. 2001. *A review of gravel addition projects on Clear Creek, the Tuolumne River, and the Stanislaus River, California: Implications for CALFED Bay-Delta Program project management*. Report to UC Berkeley Department of Landscape Architecture/Environmental Planning in partial fulfillment of requirements for the Master's Degree.

McBain and Trush. 2000. *Lower Clear Creek Floodway Rehabilitation Project. Channel Reconstruction, Riparian Vegetation, and Wetland Creation Design Document*. Prepared for the Clear Creek Restoration Team; Prepared by McBain and Trush, Graham Matthews and Associates, and North State Resources. August 2000.

Platts, W.S., W.F. Megahan, and G.W. Minshall. 1983. Methods for evaluating stream, riparian, and biotic conditions. USDA Forest Service, Intermountain Forest and Range Experimental Station, *General Technical Report INT-138*

Raleigh, R.F., W.J. Miller, and P.C. Nelson. 1986. *Habitat suitability index models and instream flow suitability curves: chinook salmon*. U.S. Fish and Wildlife Service Biological Report 82(10.122). 64 p.

Walters, C.J, and C.S. Holling. 1990. Large-scale management experiments and learning by doing. *Ecology*, 71(6) 2060:2068.

Western Shasta Resource Conservation District. 2000. *Final Report: Lower Clear Creek Spawning Gravel Restoration Projects, 1997 – 2000*. Prepared for US Bureau of Reclamation.